Upwelling: Basic Concepts and Observations

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Nansen-Nutu Summer School on Ocean, Cimate and Marine Ecosystems,
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Roadmap Upwelling

Part 1: Basic Concepts and Observations (Marcus Dengler)

Part 2: Theory and Models (Martin Schmidt)

Roadmap Part 1:

- Motivation: Upwelling and Climate
- Basic concepts
- Circulation in upwelling regions
  - Eastern boundary circulation off Northwest Africa
  - Eastern boundary circulation and eddy generation off Peru
  - Eastern boundary circulation of Angola

Roadmap Upwelling: Basic Concepts and Observations

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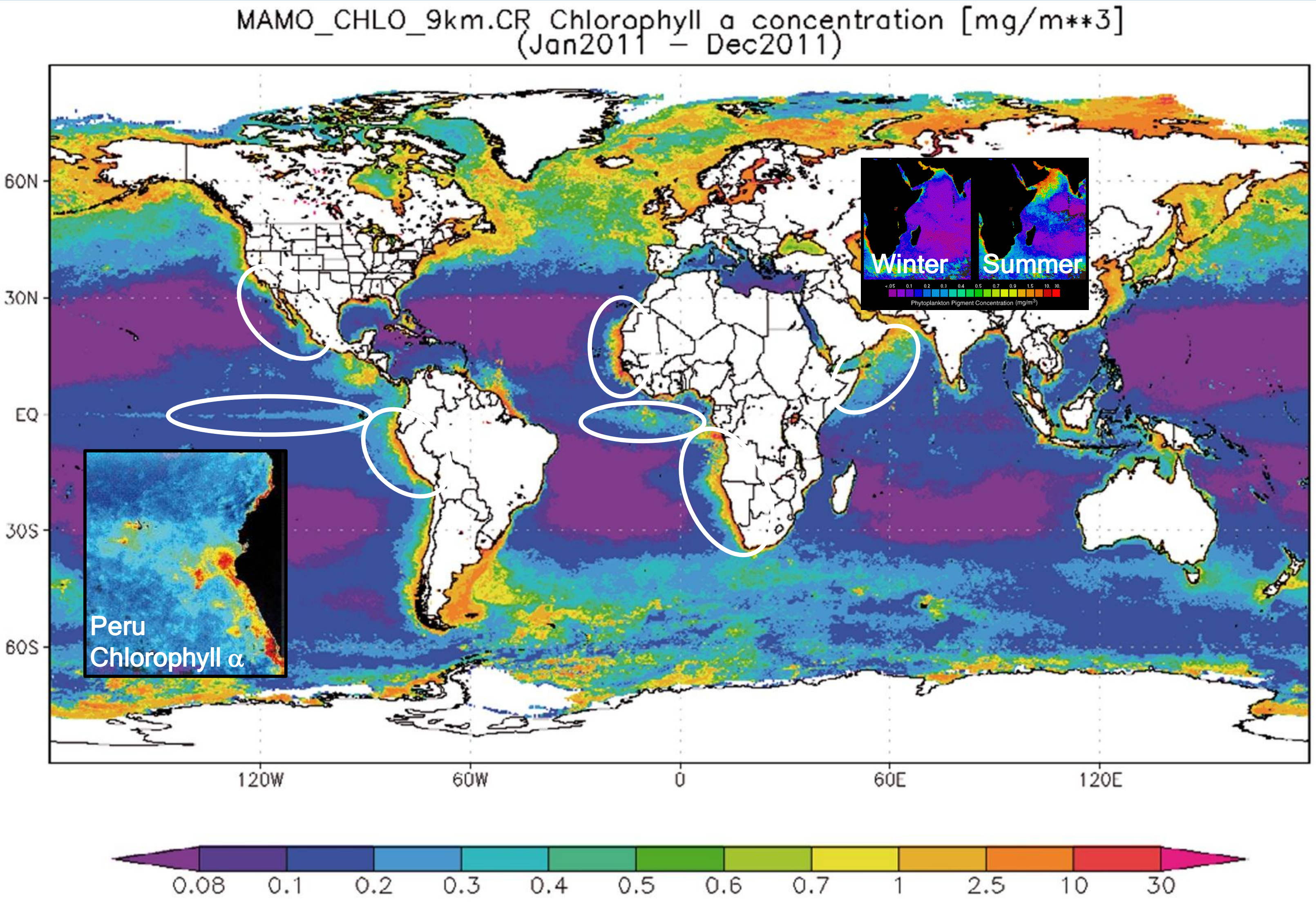
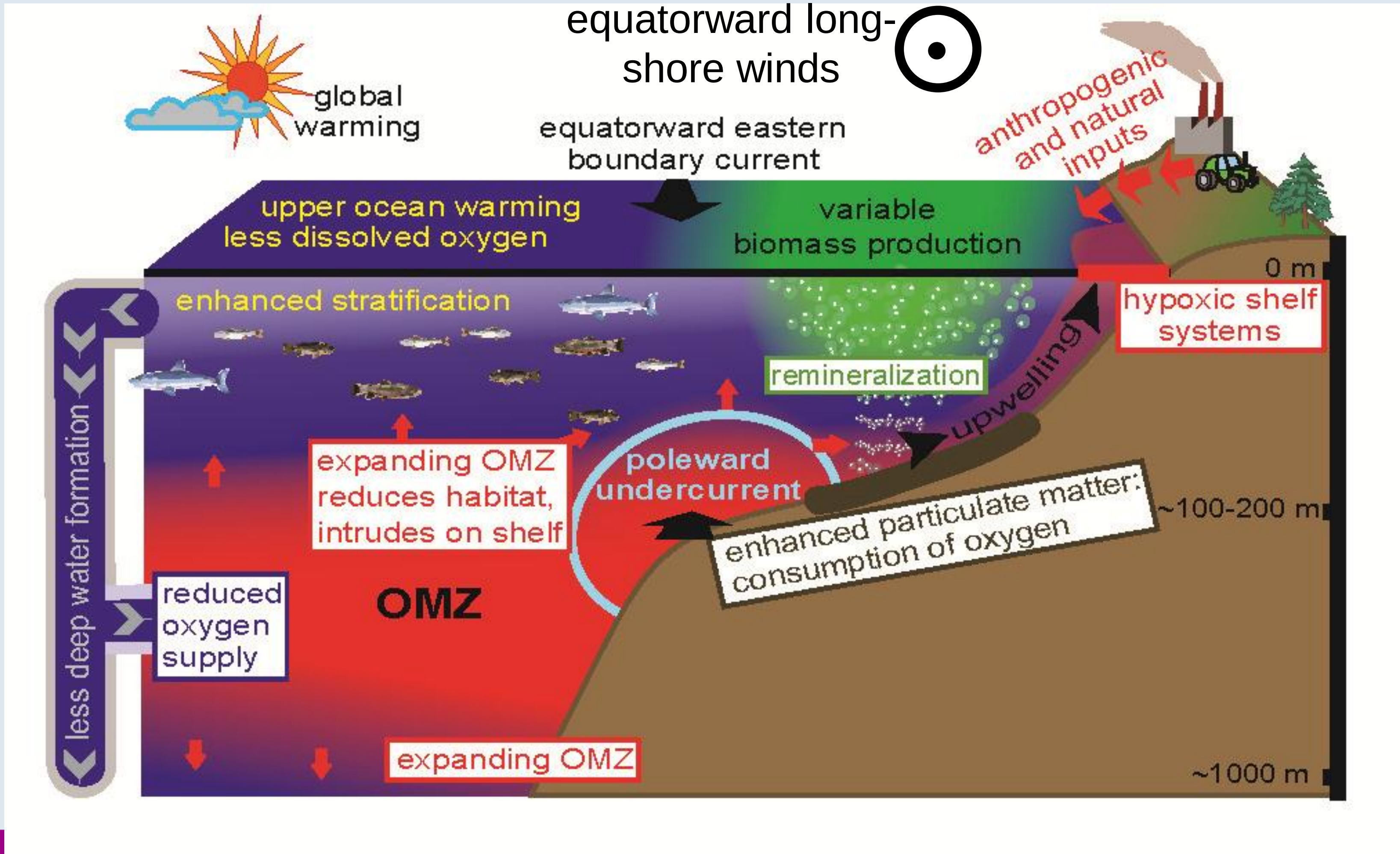
Major Tropical Upwelling Regions



Capone and Hutchins (2013)

Eastern Boundary Upwelling Systems and Climate Change



OMZ – oxygen minimum zone

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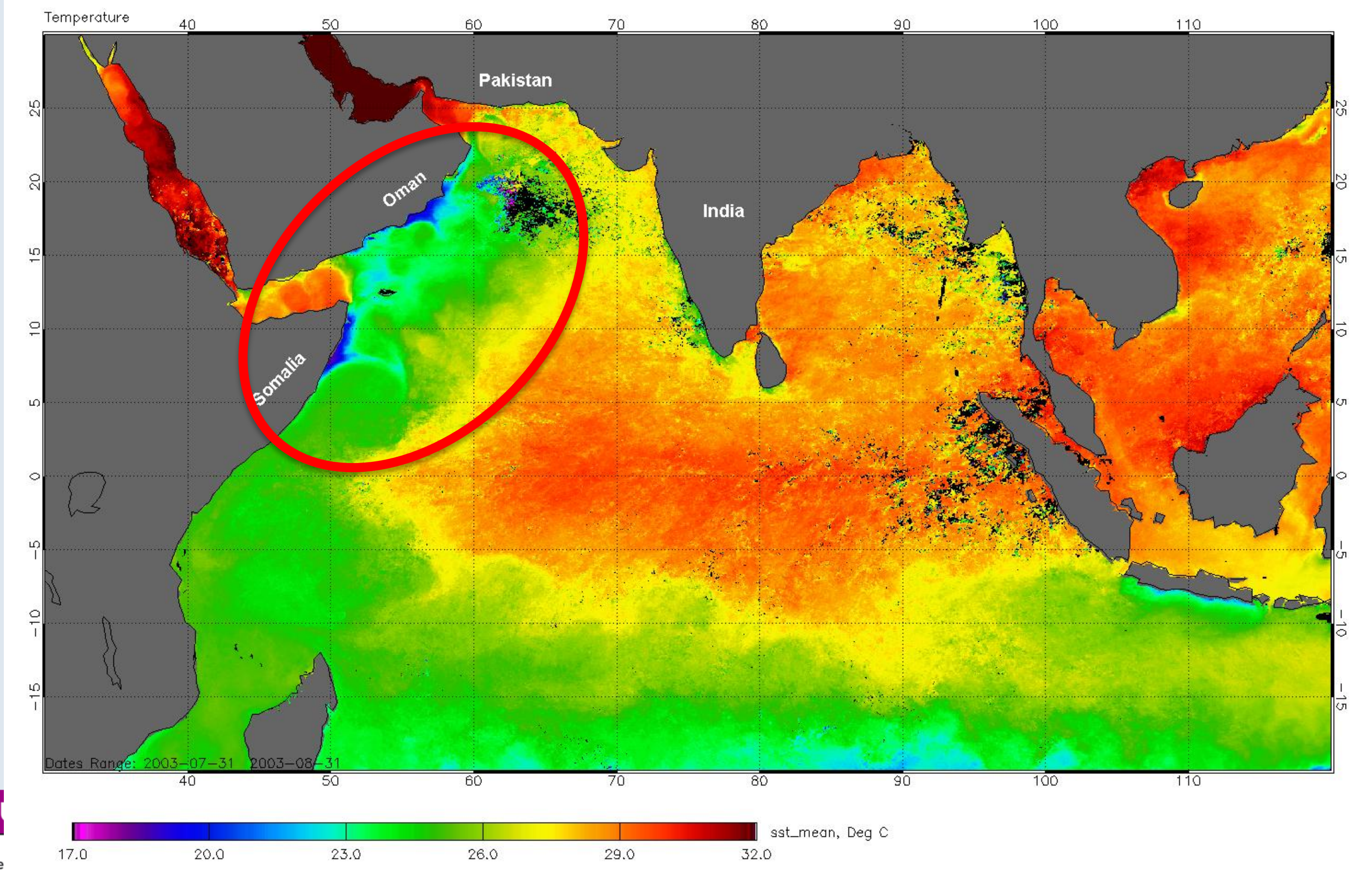
Upwelling and Climate Variability

Sea Surface Temperature (31 June 2003)



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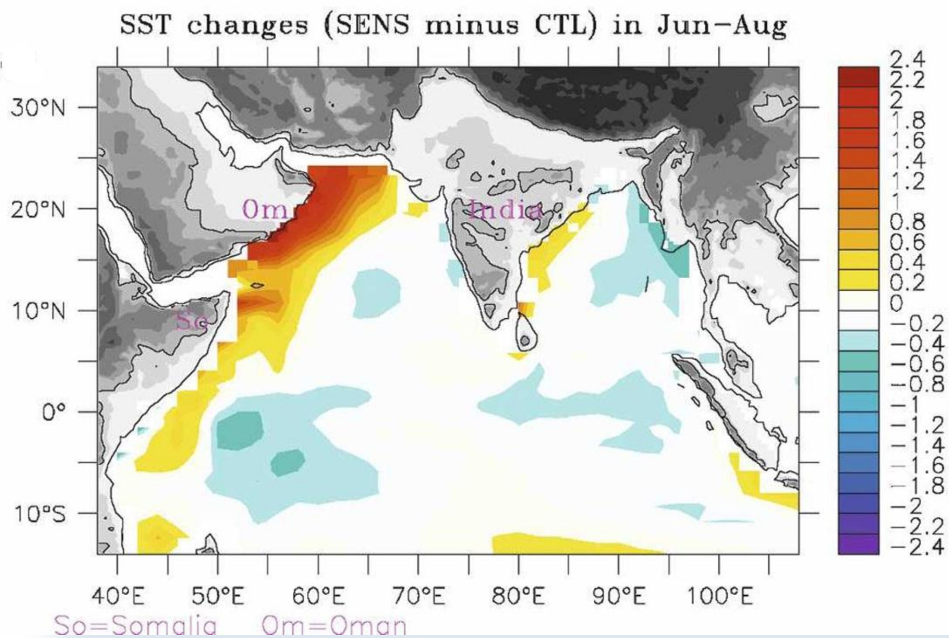
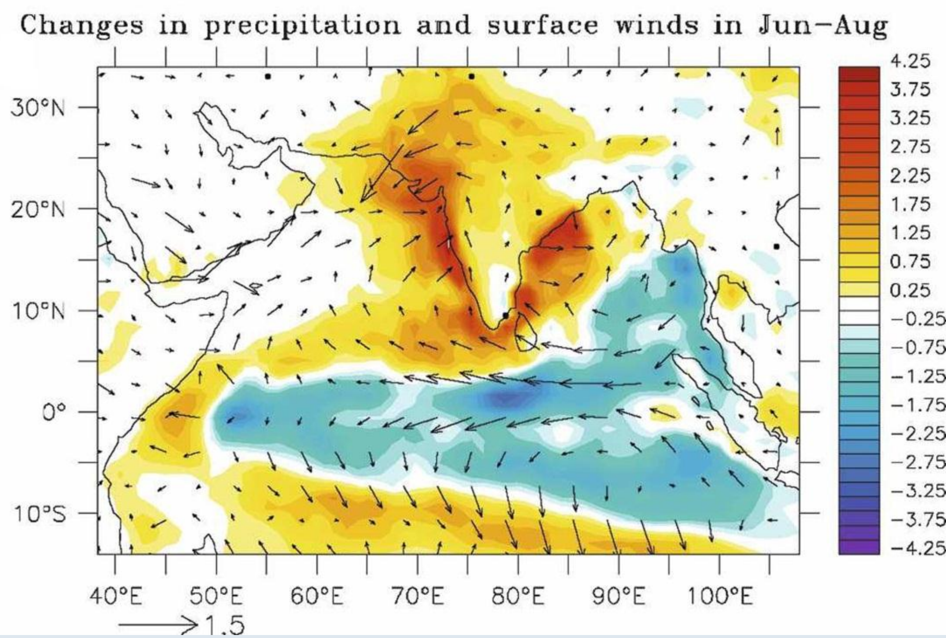
Upwelling in the Indian Ocean and Climate Variability

temperature anomaly



related precipitation anomaly



(Izumo et al., 2008)

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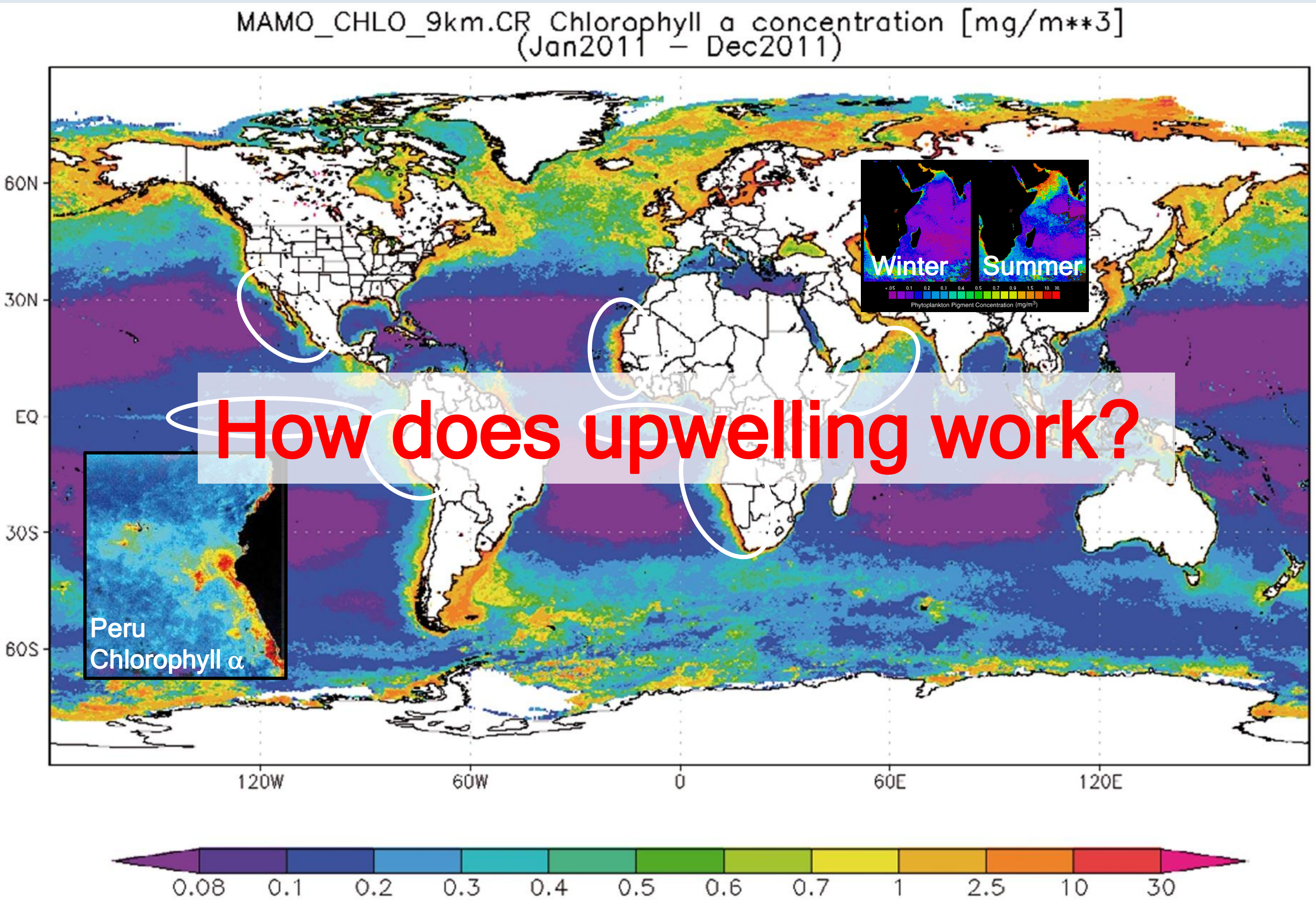
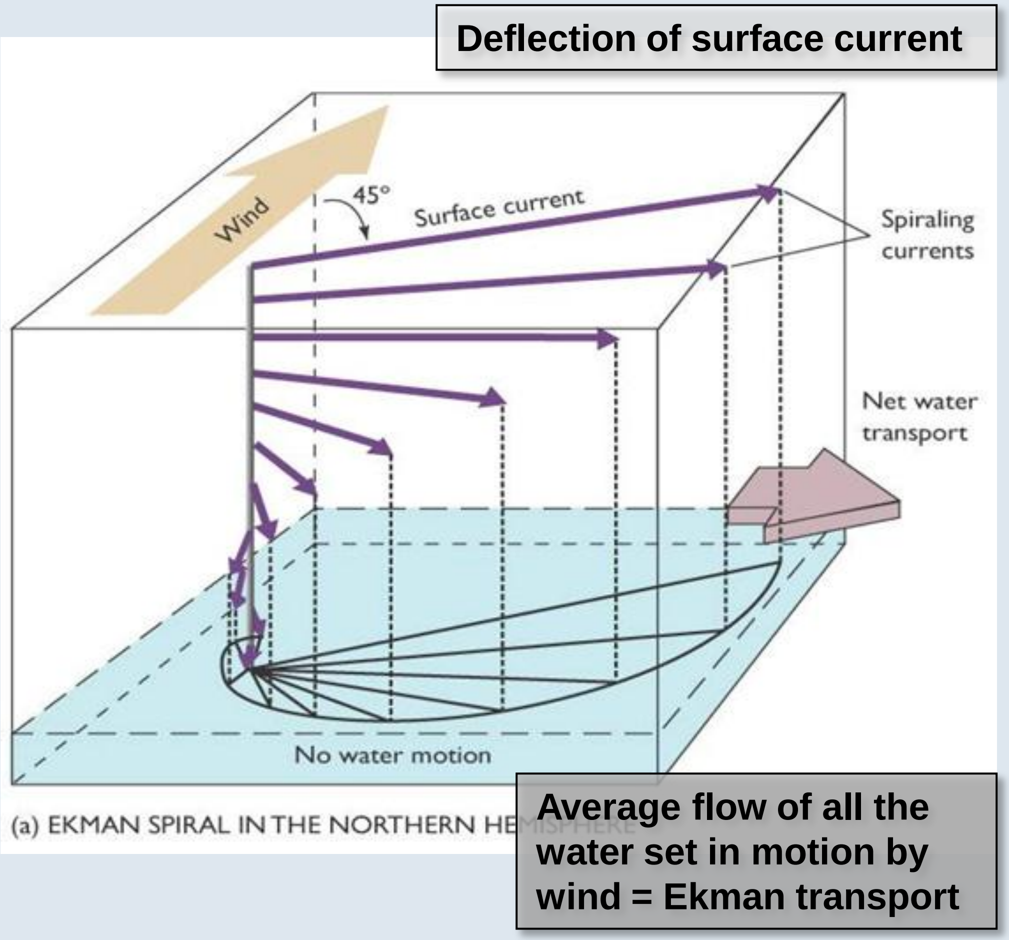
Major Tropical Upwelling Regions



Capone and Hutchins (2013)

The Basics: Ekman Transport

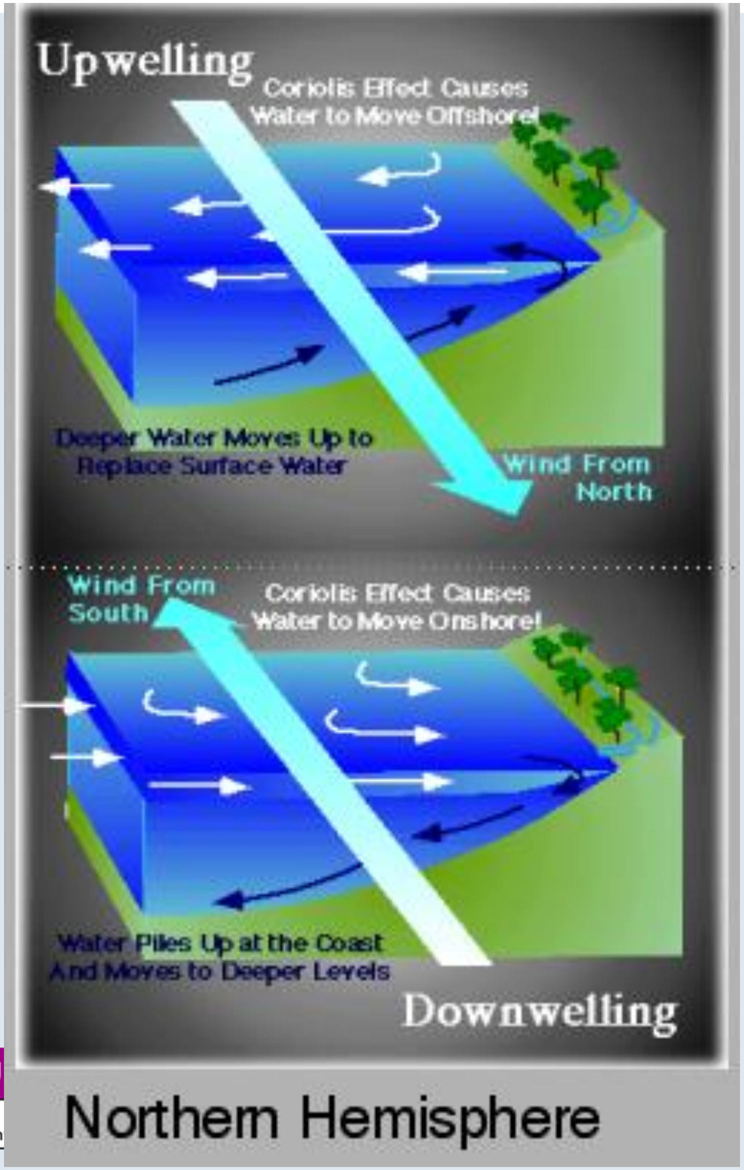
- Winds set surface waters in motion: Moving water is deflected to the right (NH).
- The effect of winds and deflection combine to create the large-scale pattern surface currents.
- Water just below the surface receives less energy, moves more slowly, and is further deflected to the right (NH)



(a) EKMAN SPIRAL IN THE NORTHERN HEMISPHERE

The direction and speed of flow change with depth to form the *Ekman spiral*. Net transport over the wind-driven column is 90º to the right of the wind (NH).

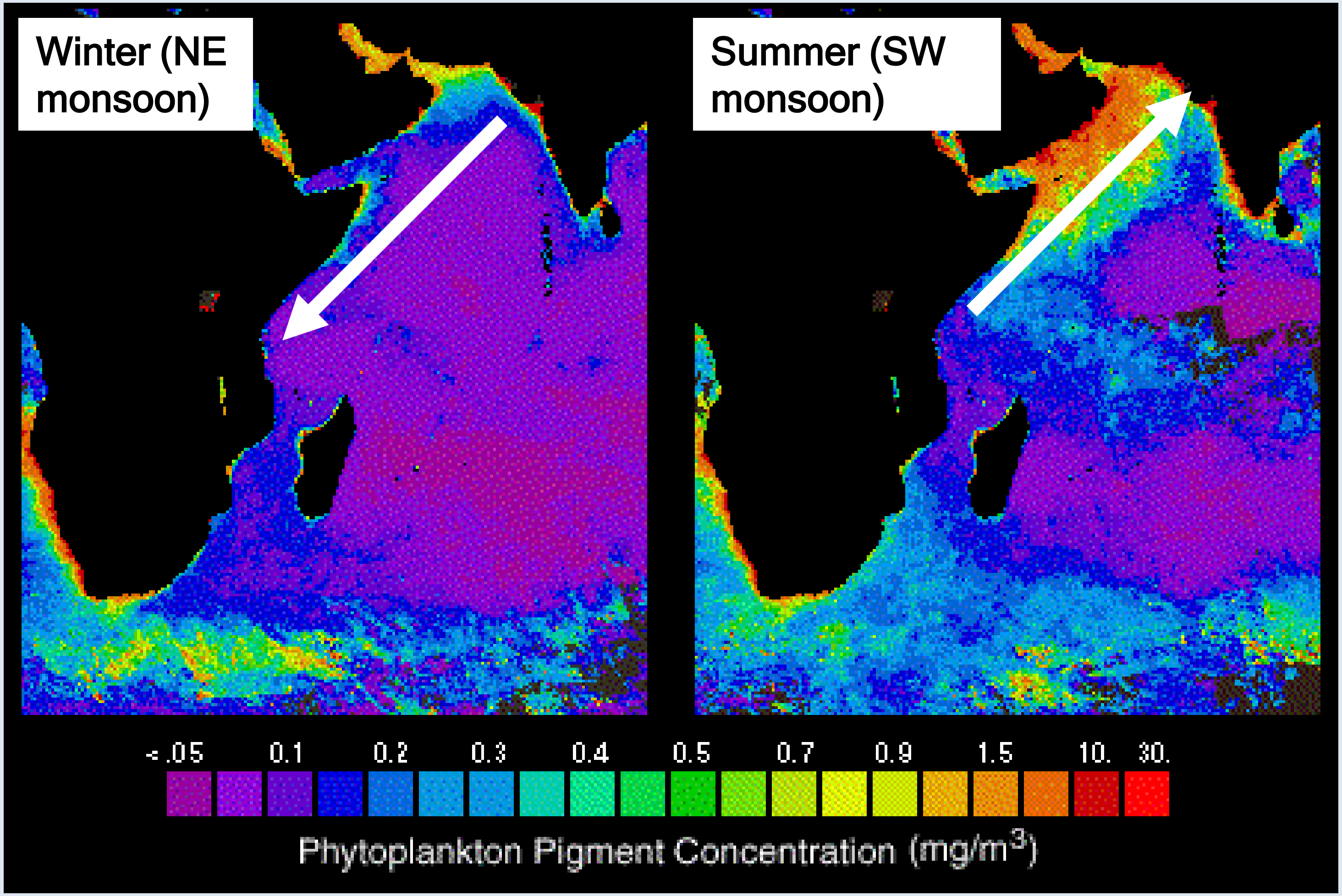
Coastal Upwelling



Wind parallel to the coast line lead to offshore (onshore) Ekman transports of water in the surface layer that

- causes upwelling (downwelling) along the coast
- drives vertical advection of nutrient-rich cold waters from the deeper layers upward to the near surface layer (or inhibits nutrient-rich waters to reach the surface layer) due to continuity
- leads to high (low) productivity in the upwelling region

Seasonal Upwelling in the Indian Ocean



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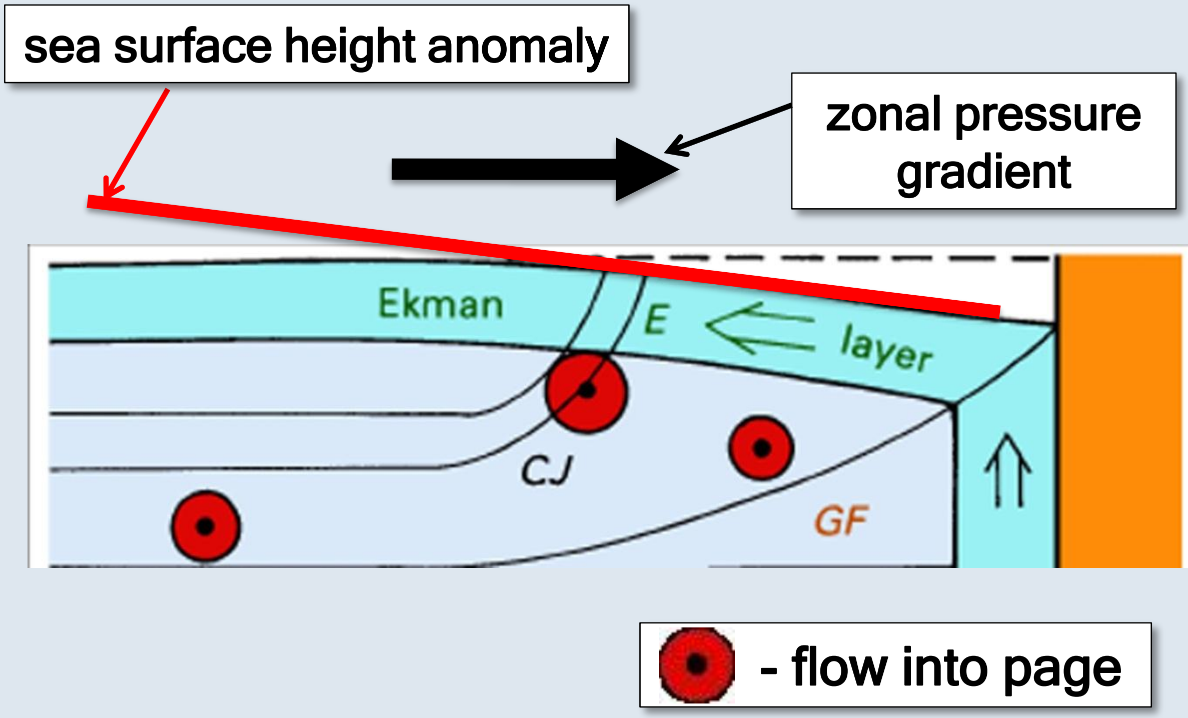
The Basics: Coastal Upwelling and Equatorward Surface Flow

- The offshore Ekman transports is opposed by a zonal tilt in sea surface height generating a pressure gradient towards the coast.
- This zonal pressure gradient is balanced by the Coriolis force causing a geostrophic equatorward surface flow on the shelf.



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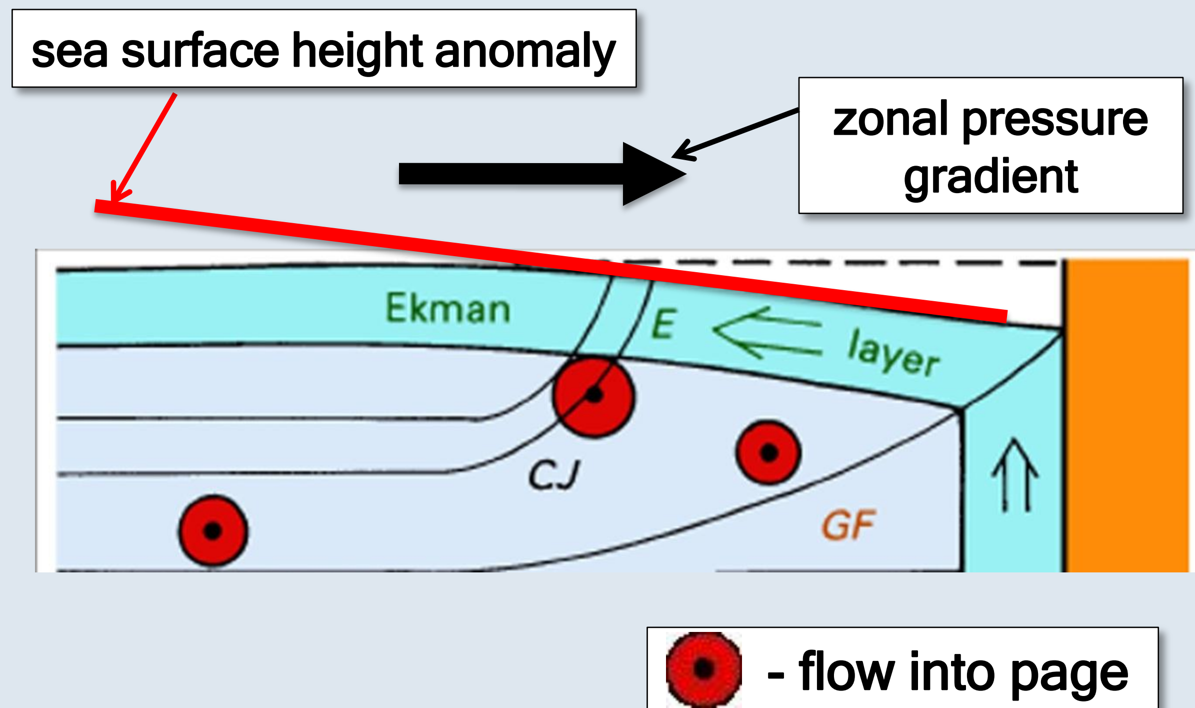
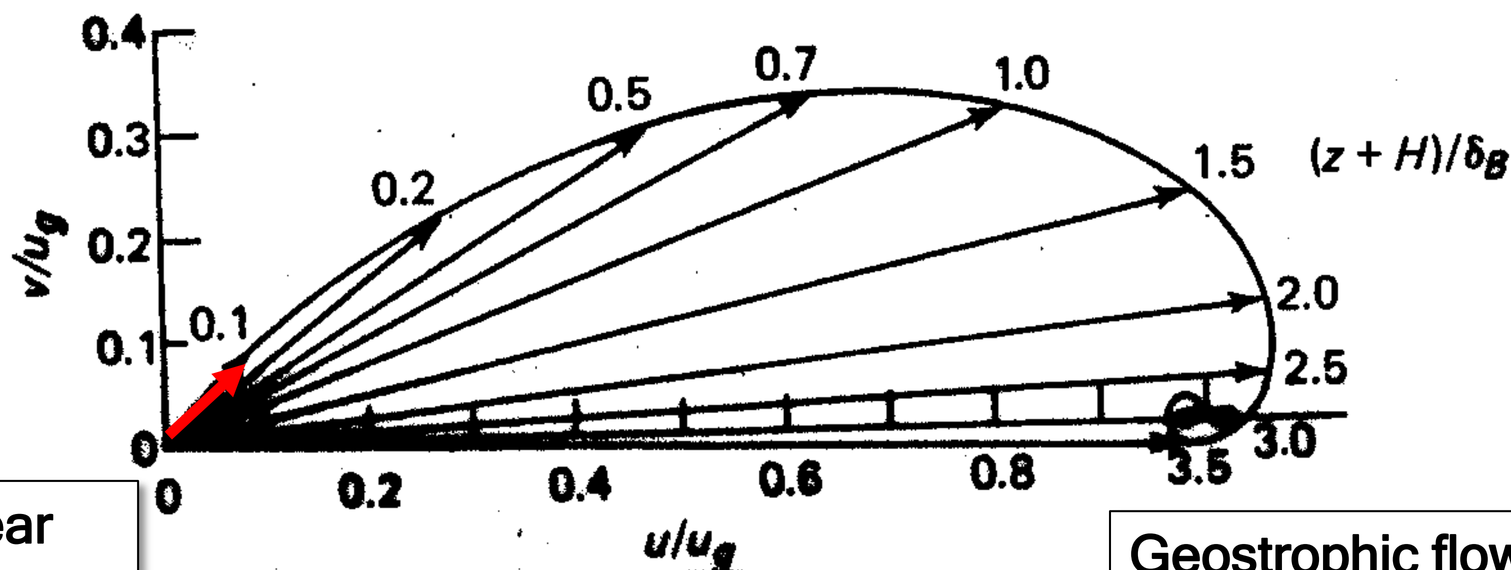


Where does the upwelled water come from?

The Basics: Ekman Balance of the Bottom Boundary Layer



Flow near the bottom boundary

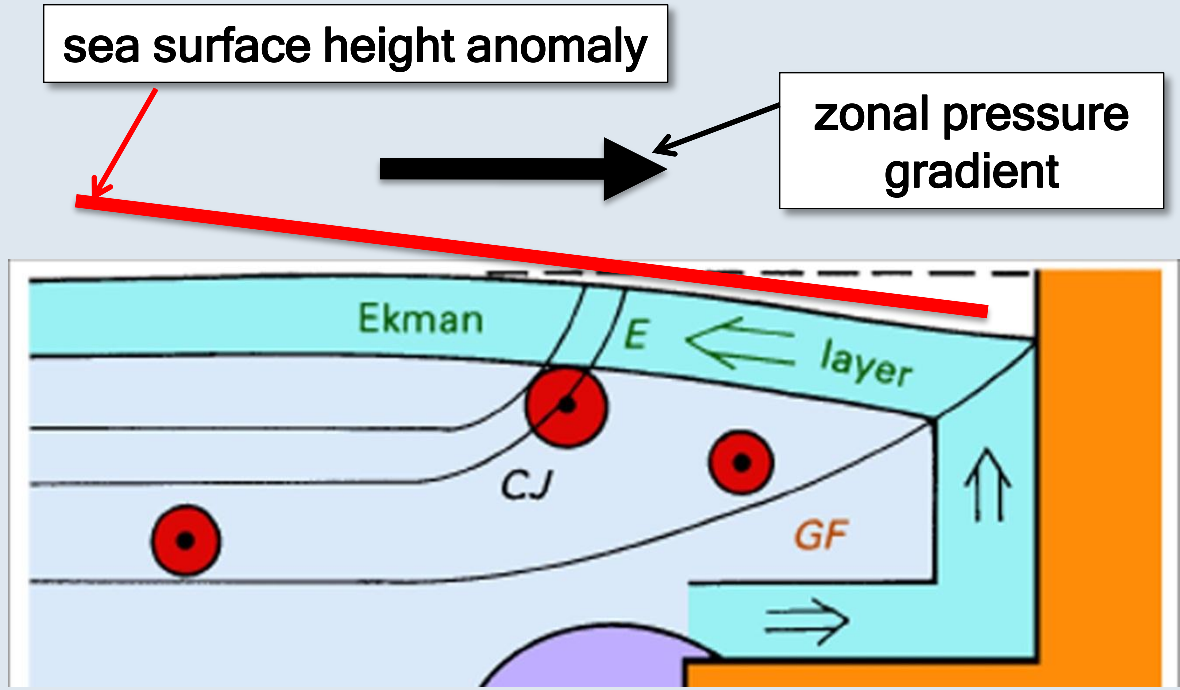
Geostrophic flow above the bottom boundary layer

If a geostrophic current is situated above the sea floor, an Ekman spiral will be formed in the bottom boundary layer, except that here the flow is deflected to the left (NH).

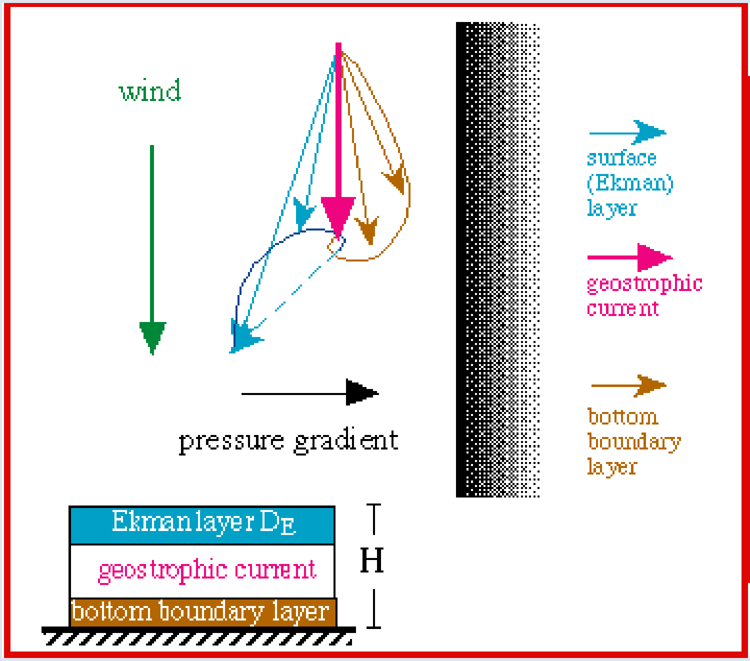
(Stewart, 2003)

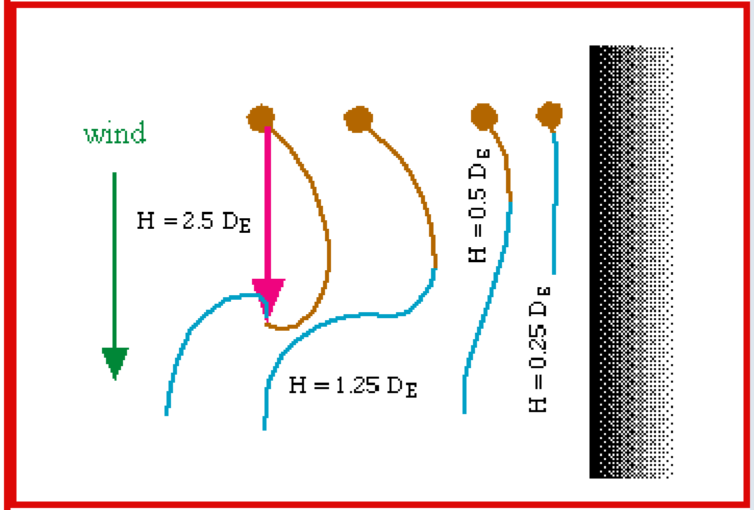
The Basics: Coastal Upwelling and Equatorward Surface Flow

The equatorward flow forces an onshore flow in the bottom boundary layer that supplies the coastal upwelling.

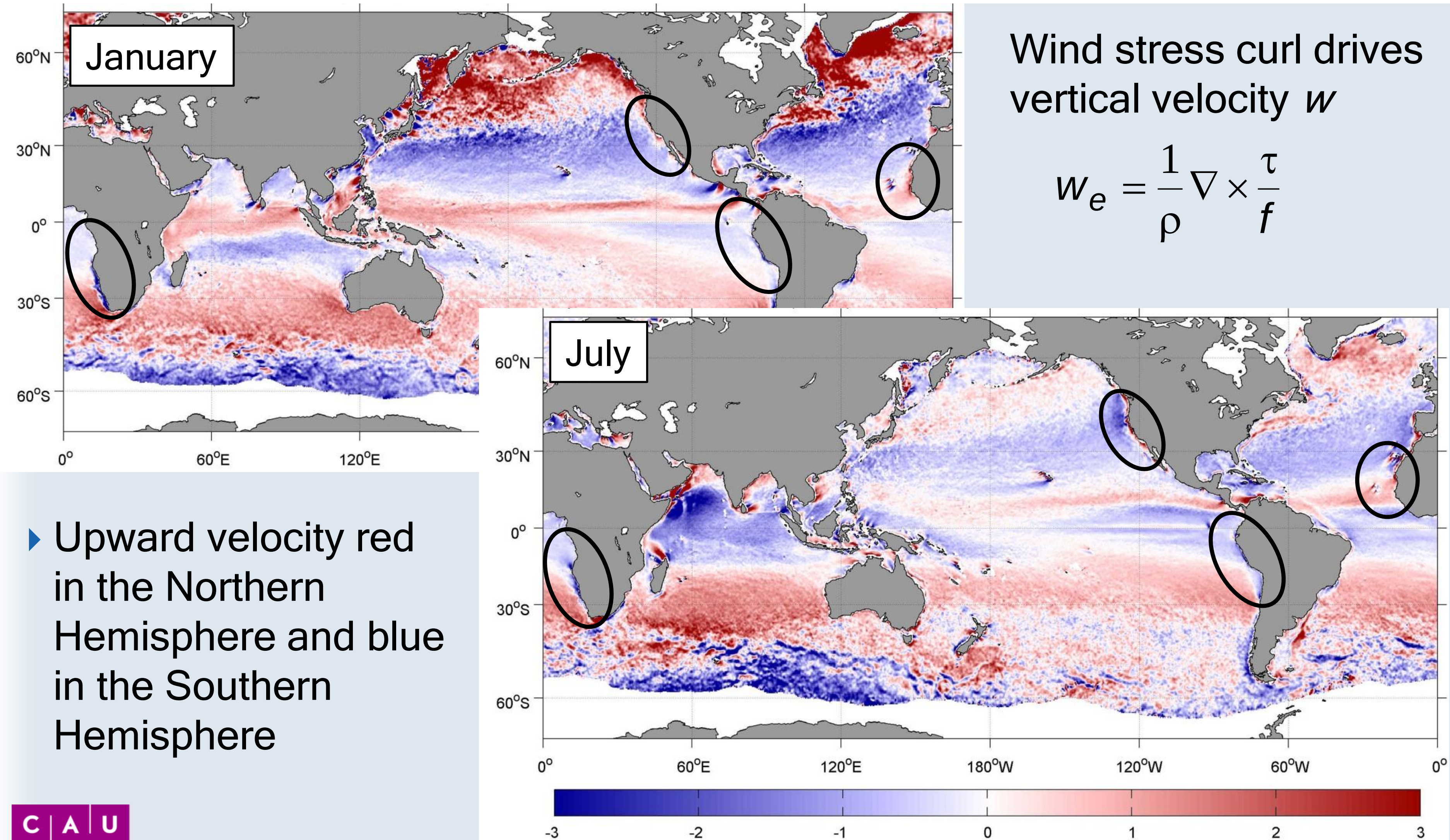


The Basics: Coastal Upwelling and Equatorward Surface Flow





Global Wind Stress Curl and Upwelling



Wind stress curl drives vertical velocity w

$$w_e = \frac{1}{\rho} \nabla \times \frac{\tau}{f}$$

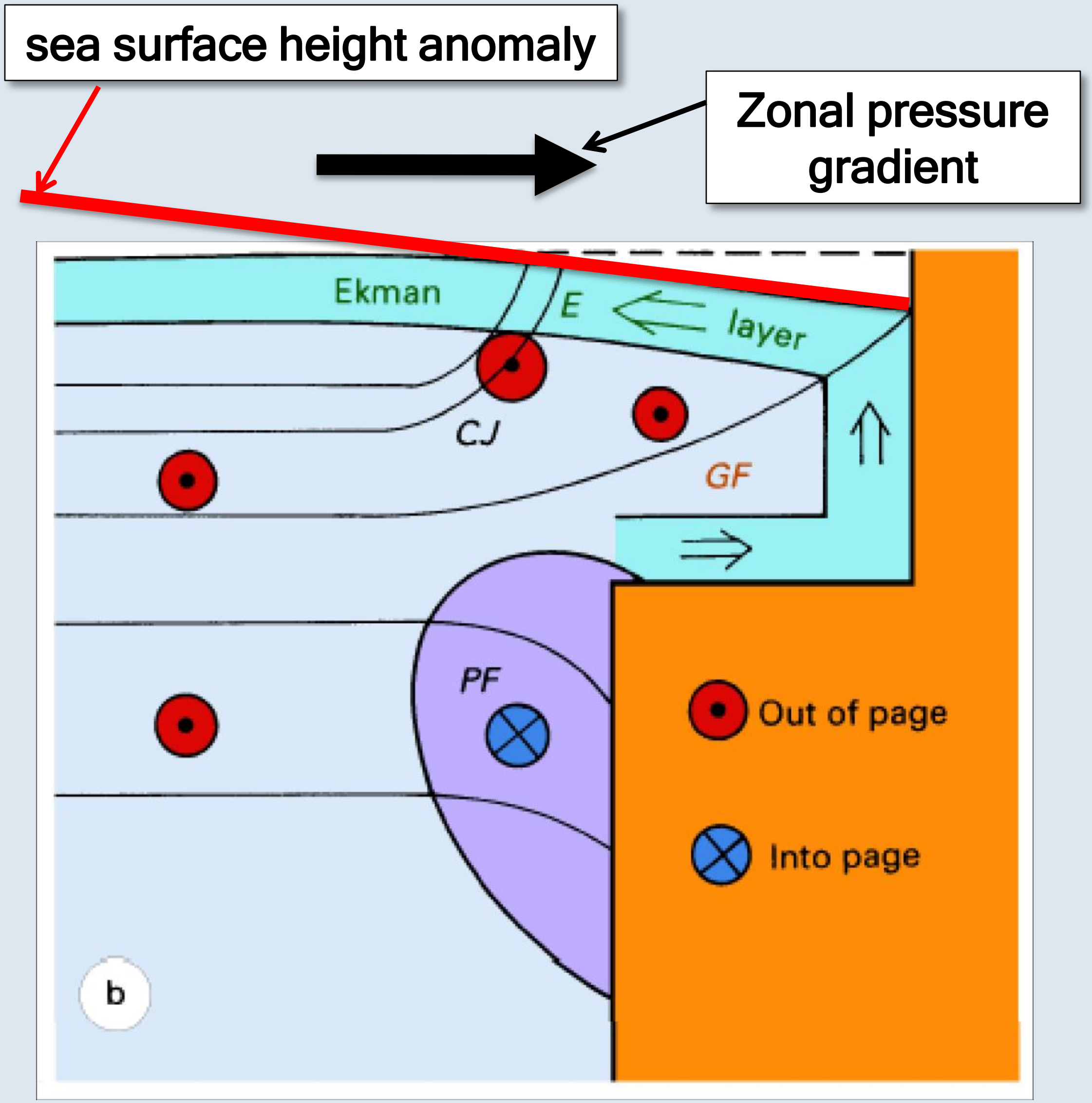
- Upward velocity red in the Northern Hemisphere and blue in the Southern Hemisphere

(Risien & Chelton, 2008)

in Nm^{-2} / 10^4 km

Upwelling and Eastern Boundary Currents

The last ingredient, the wind stress curl, additionally contributes to upwelling in the EBUS. It also contributes to forcing of a poleward undercurrent (PF) that results from a large-scale poleward pressure gradient set up by the winds.



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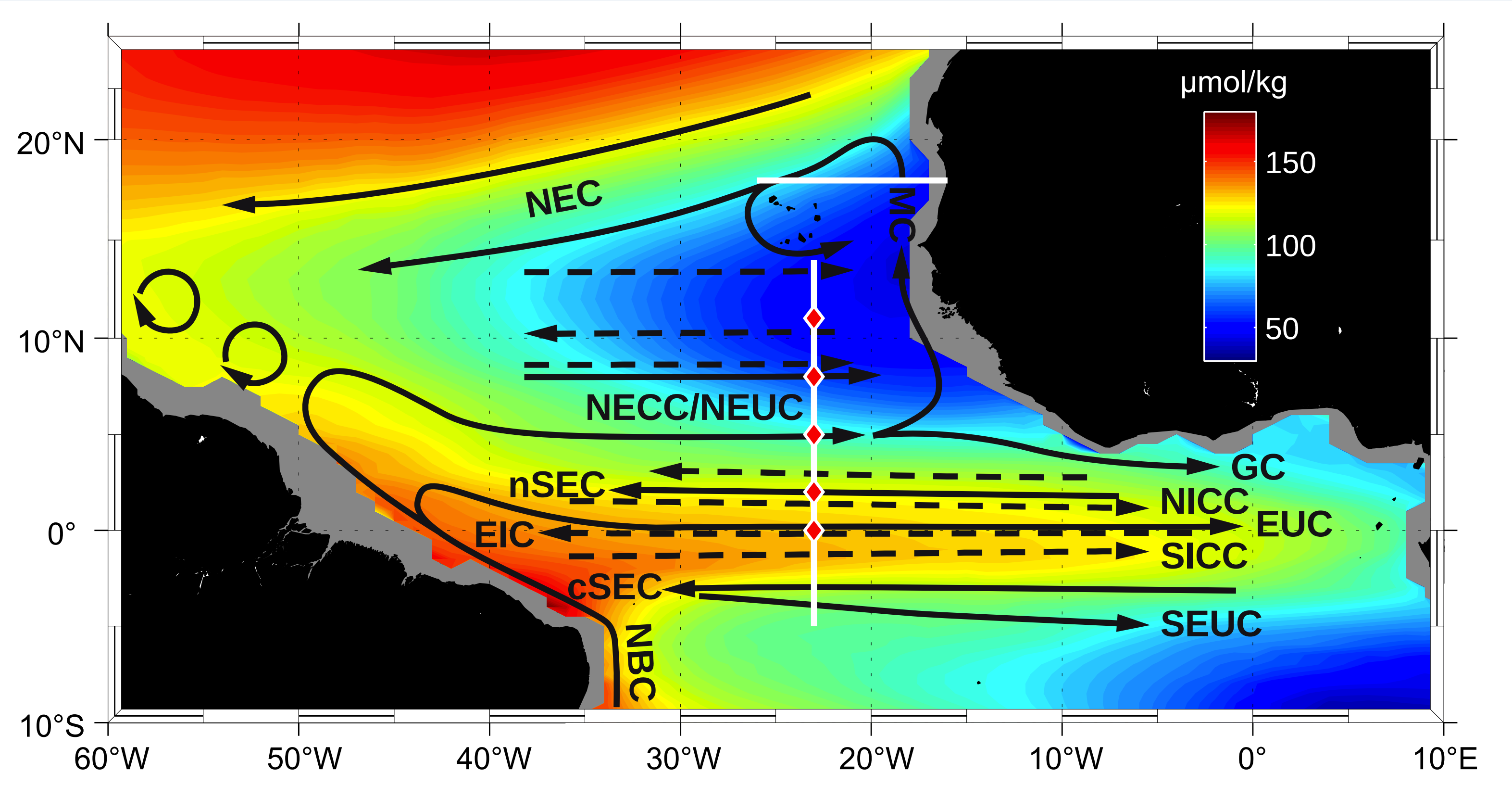
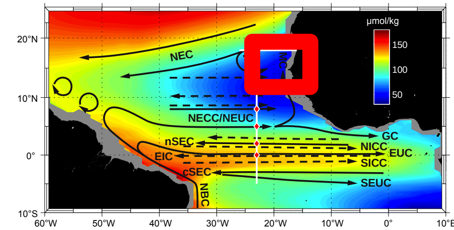
Eastern Boundary Circulation off Northwest Africa

Schematic Circulation Oxygen on σ_θ=27.1 kg m^{-3} (300-600m)

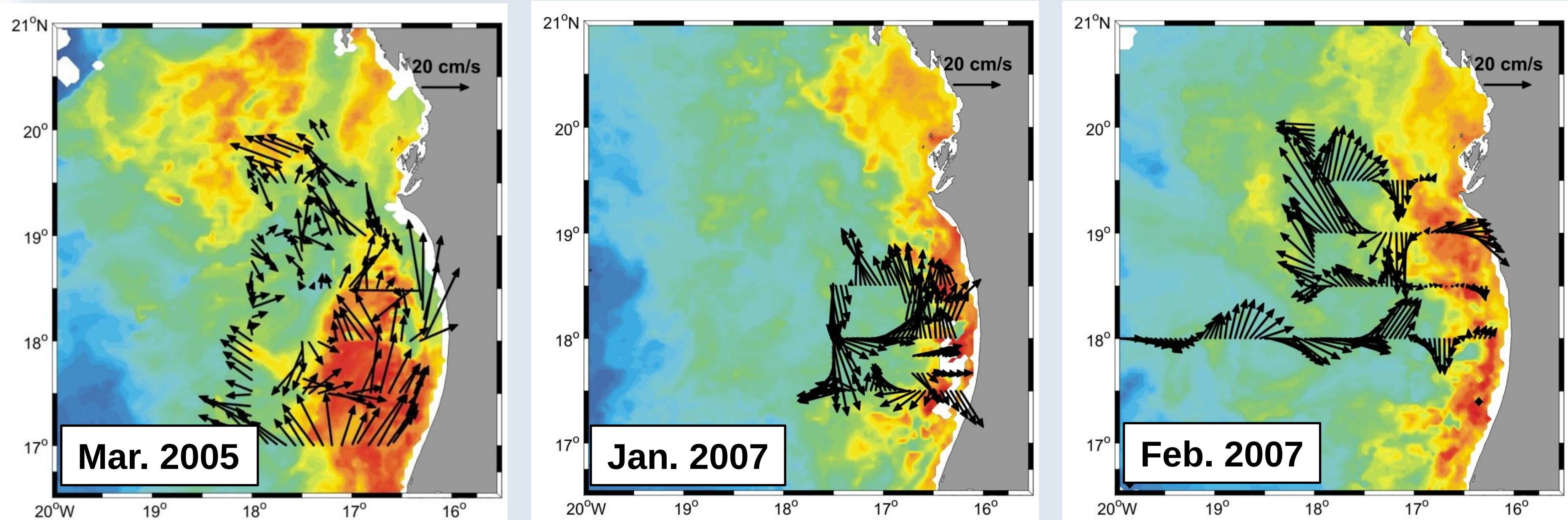


(Brandt et al., 2014)

Eastern Boundary Circulation off Mauritania



Near surface currents (20-70m) and chlorophyll during upwelling season



(Schafstall, 2010)

Strong variability of near surface currents due to

- Mesoscale eddy activity
- Coastal Kelvin Waves

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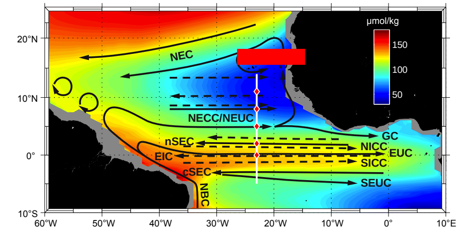
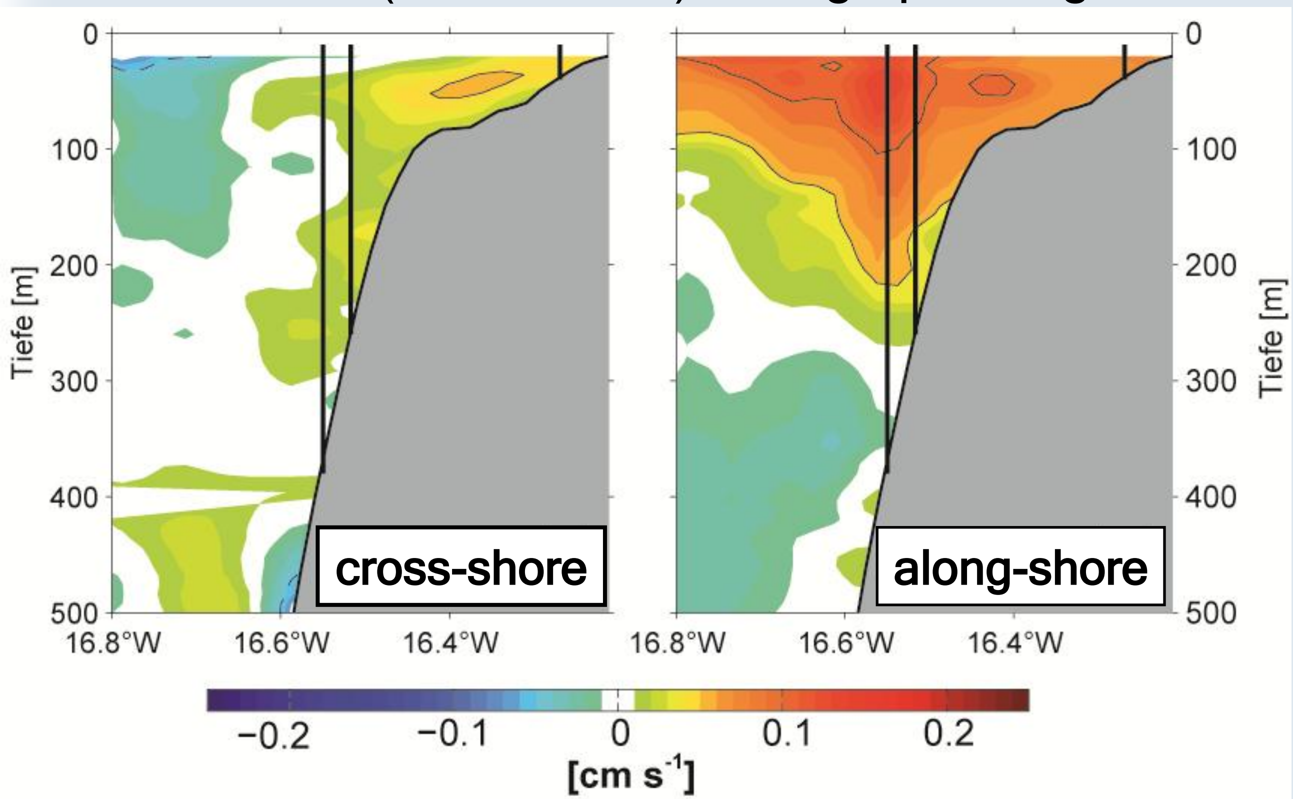
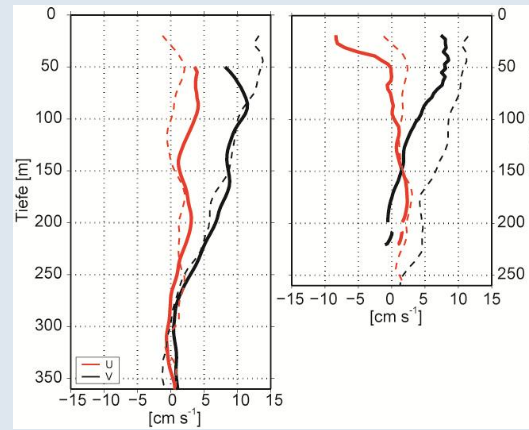
Eastern Boundary Circulation off Mauritania



Average velocity section (17.5°N-18.5°N) from 4 cruises (11 Sections) during upwelling



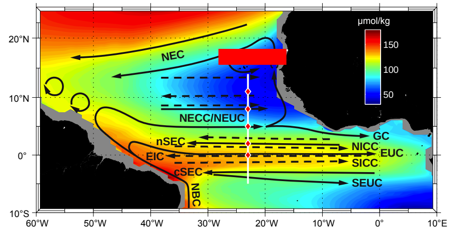
Velocity time series from moorings



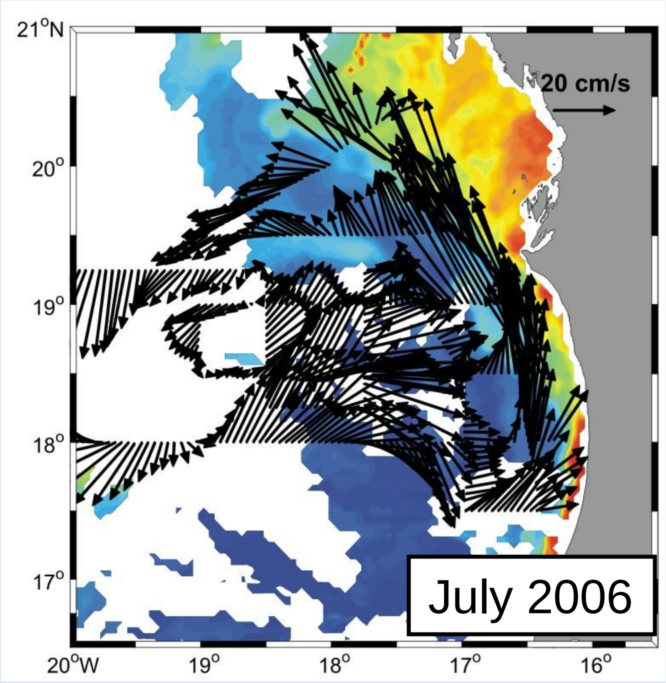
(Schafstall, 2010)

- Average circulation does not show an equatorial surface current
- Instead, poleward flow extends to the surface

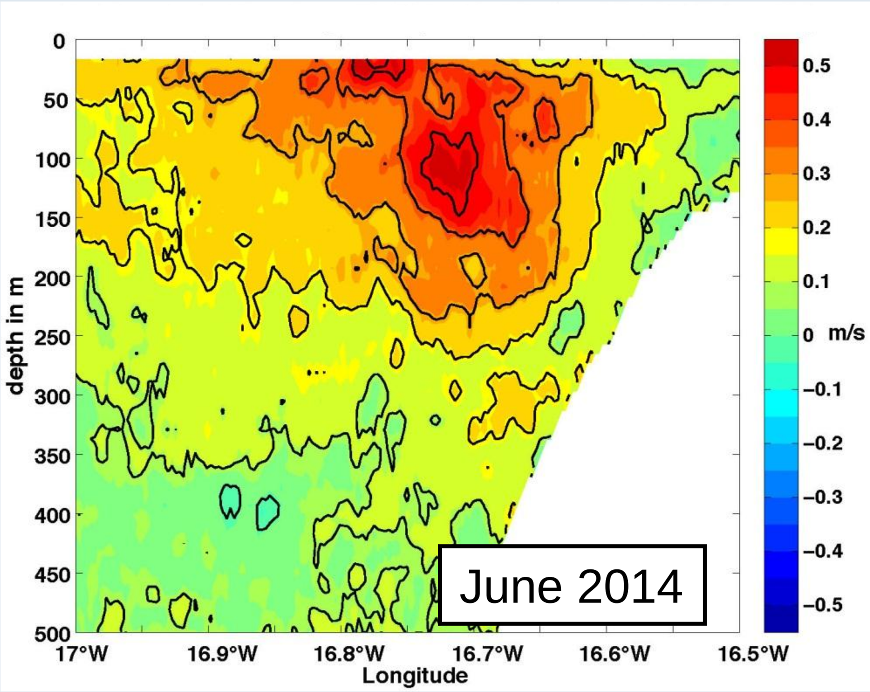
Eastern Boundary Circulation off Mauritania



Near surface currents (20-70m) and chlorophyll during non-upwelling season



Northward flow from a single section (18°N) during non-upwelling

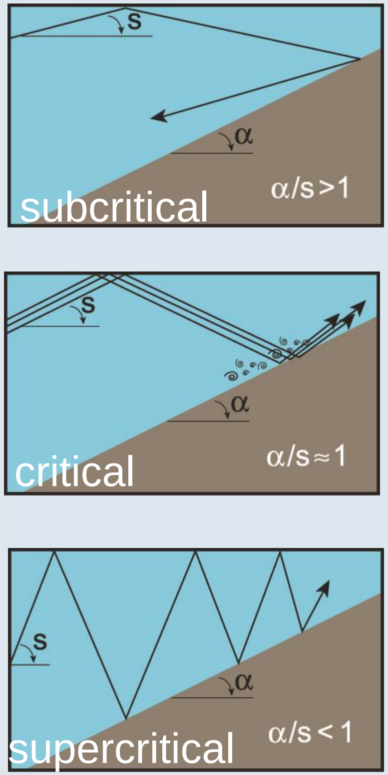


- Boundary circulation intensifies during the non-upwelling season in boreal summer

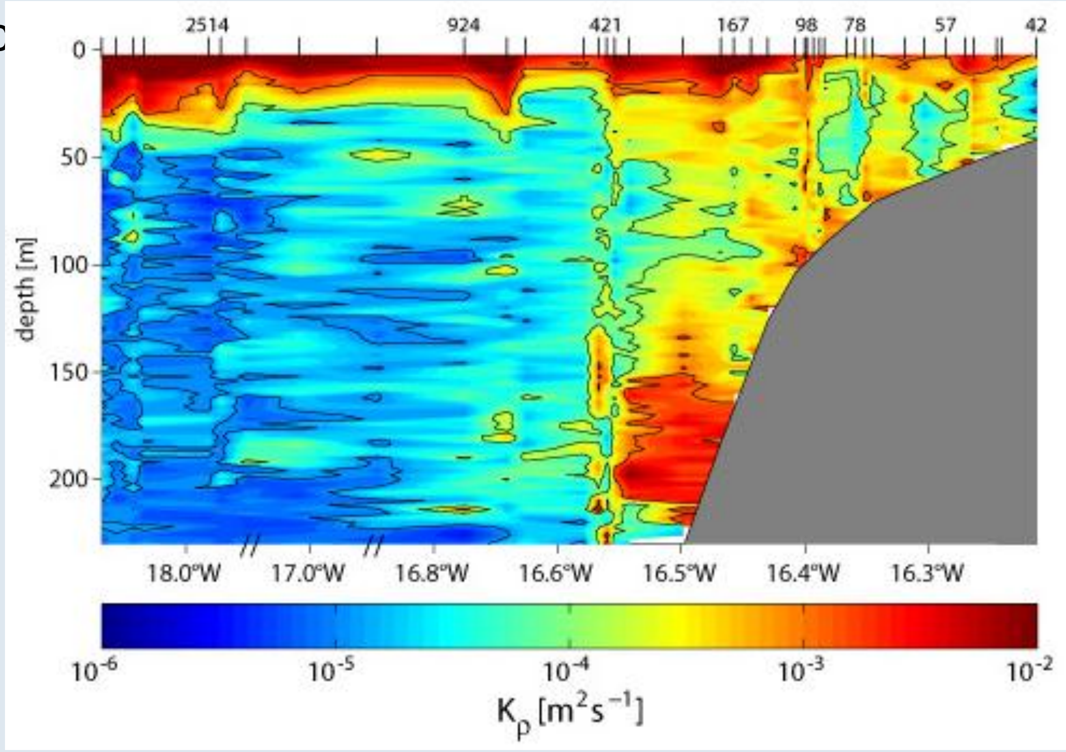
Diapycnal mixing on the continental slope and shelf

slope of the linear internal tide characteristic

$$s = \left(\frac{\sigma^2 - f^2}{N^2 - \sigma^2}\right)^{1/2}$$



(after Cacchione et al., 2002)

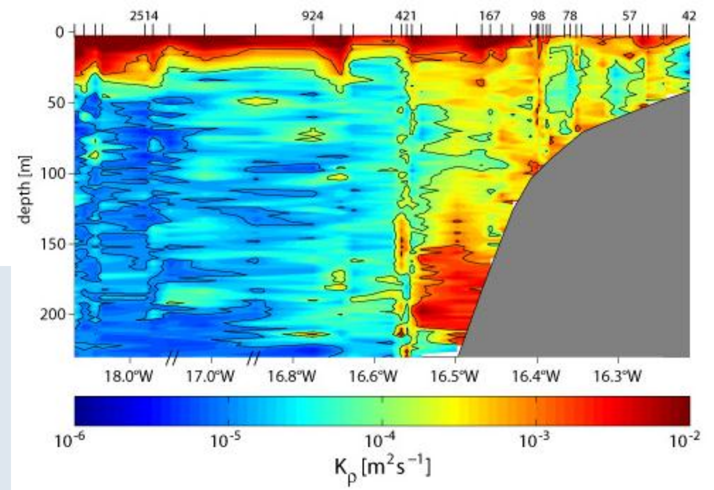


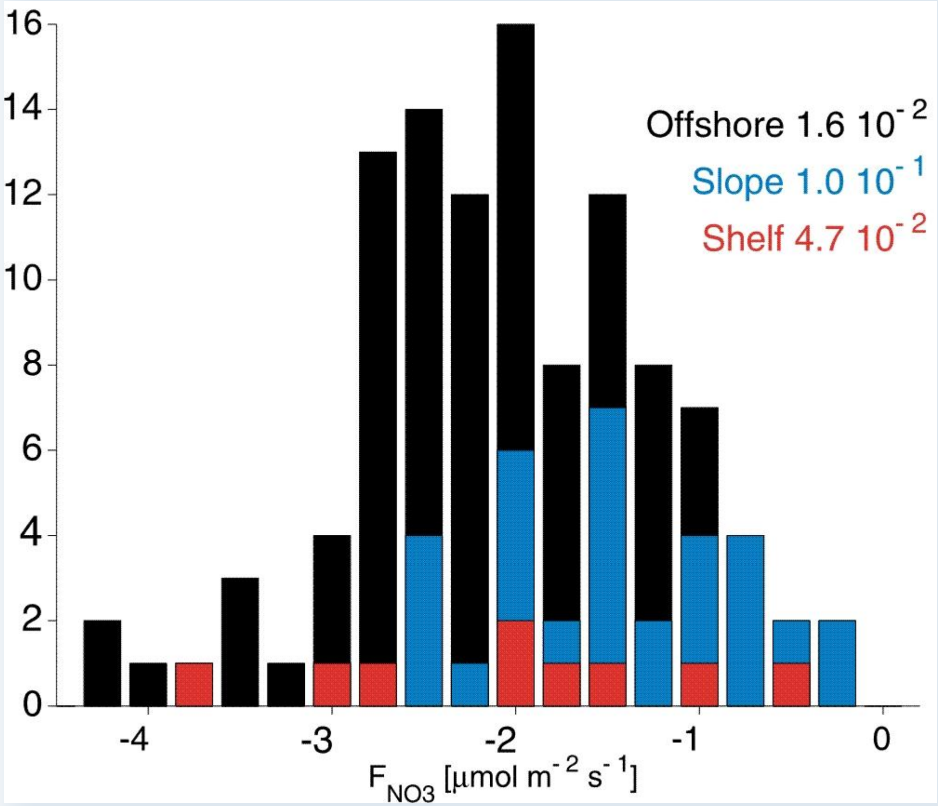
(Schafstall et al., 2010)

- Mixing on the Mauritanian continental slope is enhanced due to non-linear waves generated by tide-topography interaction

Nutrient flux due to turbulent mixing

$$Flux_{NO_3} = K_\rho \frac{d[NO_3]}{dz}$$





- Diapycnal nutrient flux contributes between 20%-80% of the required nutrient flux for primary production off Mauritania

(Schafstall et al., 2010)

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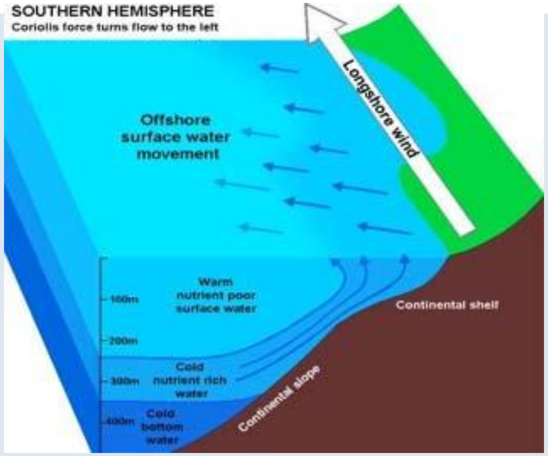
The Peruvian Upwelling Region (North of 15°S)

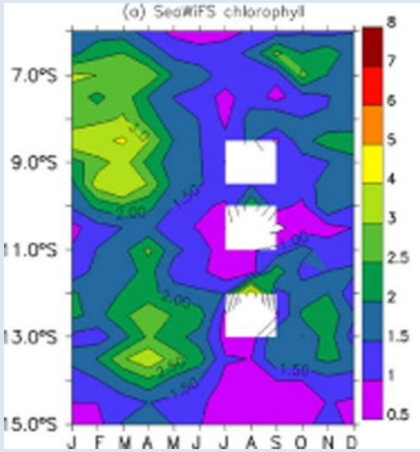


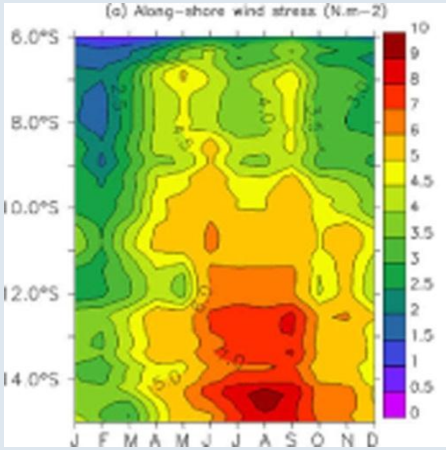
<u>Austral summer (November-April)</u>

- Seasonal minimum of alongshore wind stress & wind stress curl
- Chlorophyll maximum
- Maximum in SST
- Maximum in onshore-offshore SST gradient

<u>Austral winter (June-August)</u>

- Seasonal maximum of alongshore wind stress & wind stress curl
- Chlorophyll minimum
- Minimum in SST
- Minimum in near shore-offshore SST gradient





(Echevin et al., 2008)

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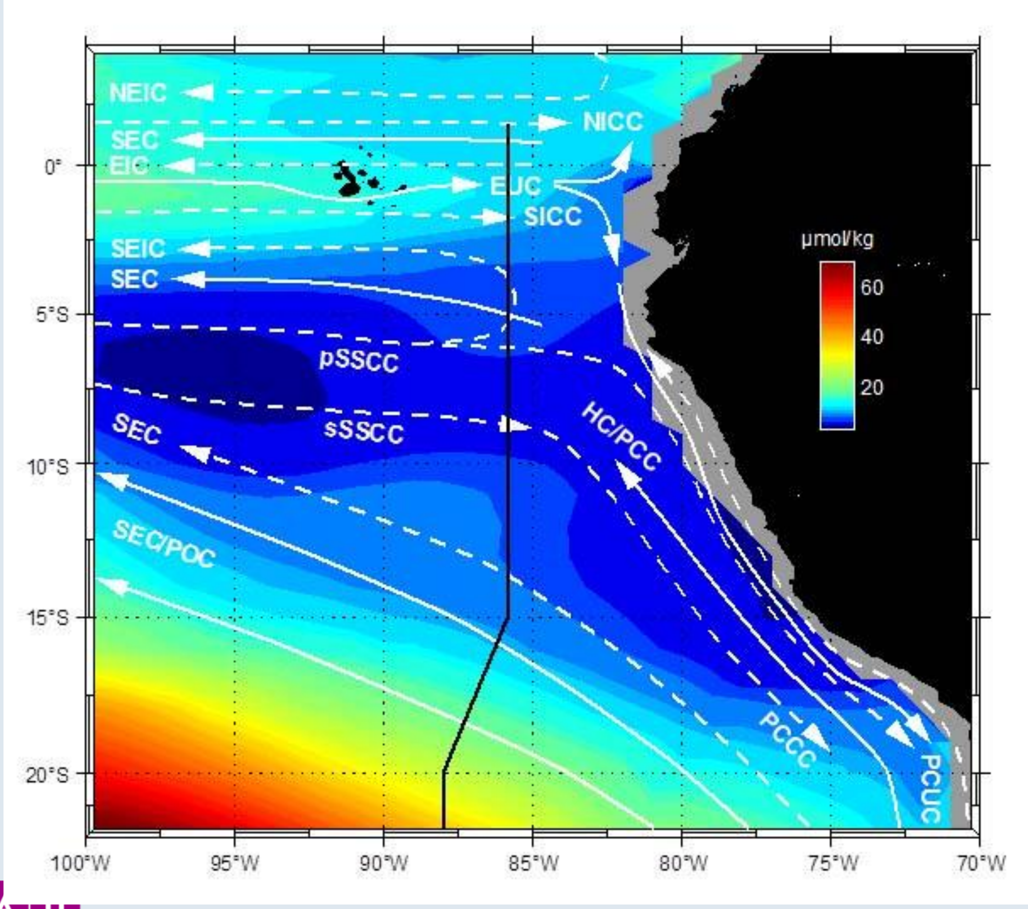
Eastern Boundary Circulation off Peru

Schematic circulation and oxygen on
σ_θ=26.8 kg m^{-3} (200-500m)



(Brandt et al., 2014)

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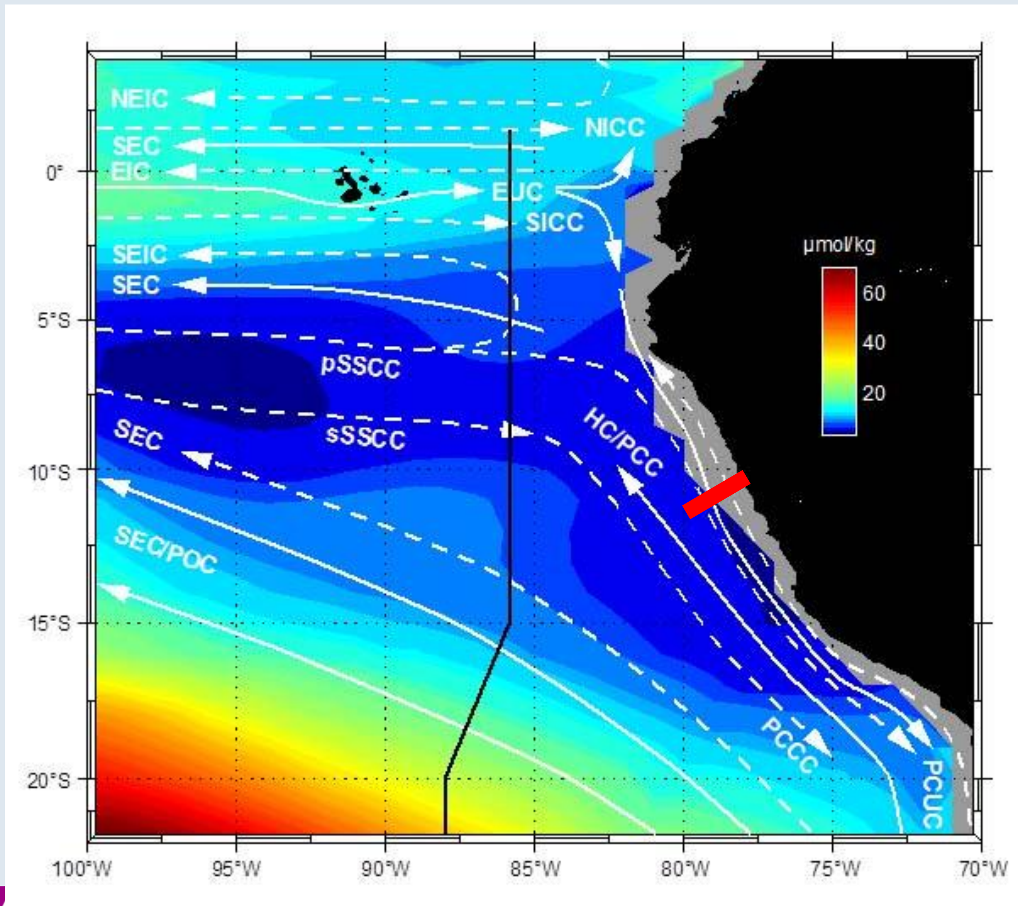
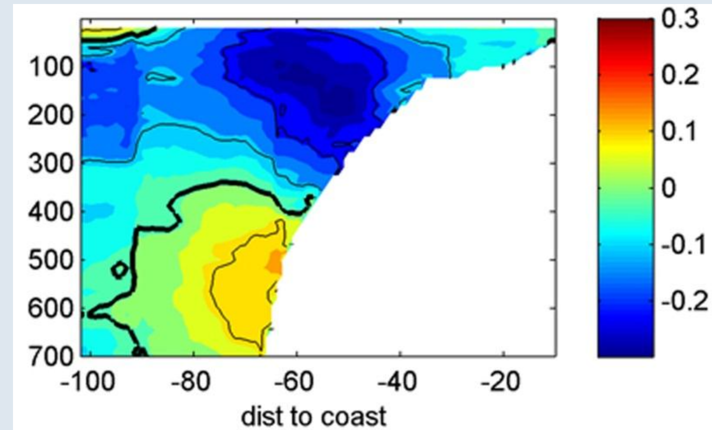


(Brandt et al., 2014)

Along-shore velocity at 12°S (5-day average Jan. 2013)



(Thomsen et al., 2014 in prep.)

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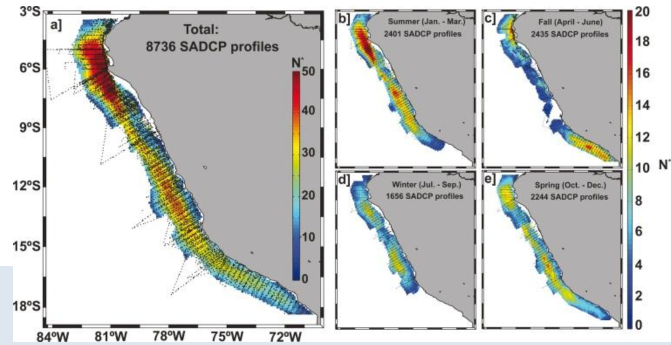
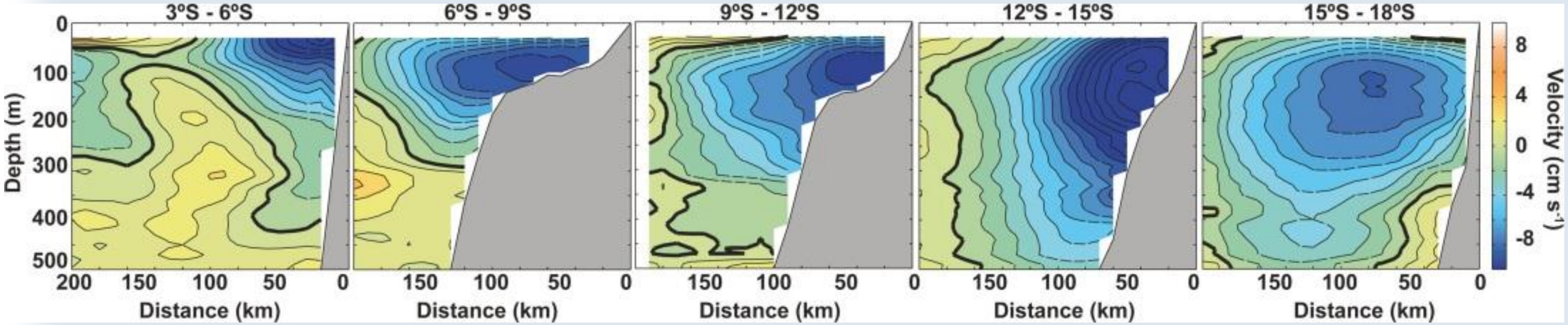
Eastern Boundary Circulation off Peru



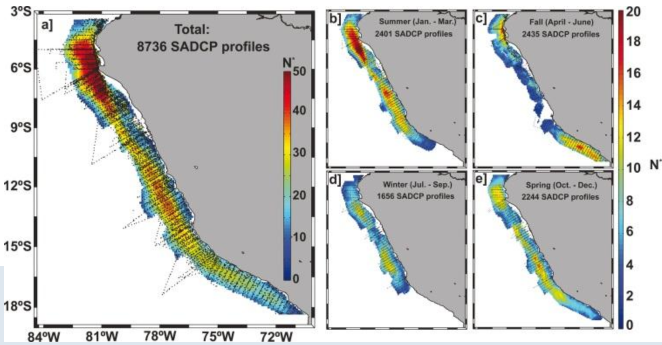
Average velocity sections from 21 cruises (2008-2012)

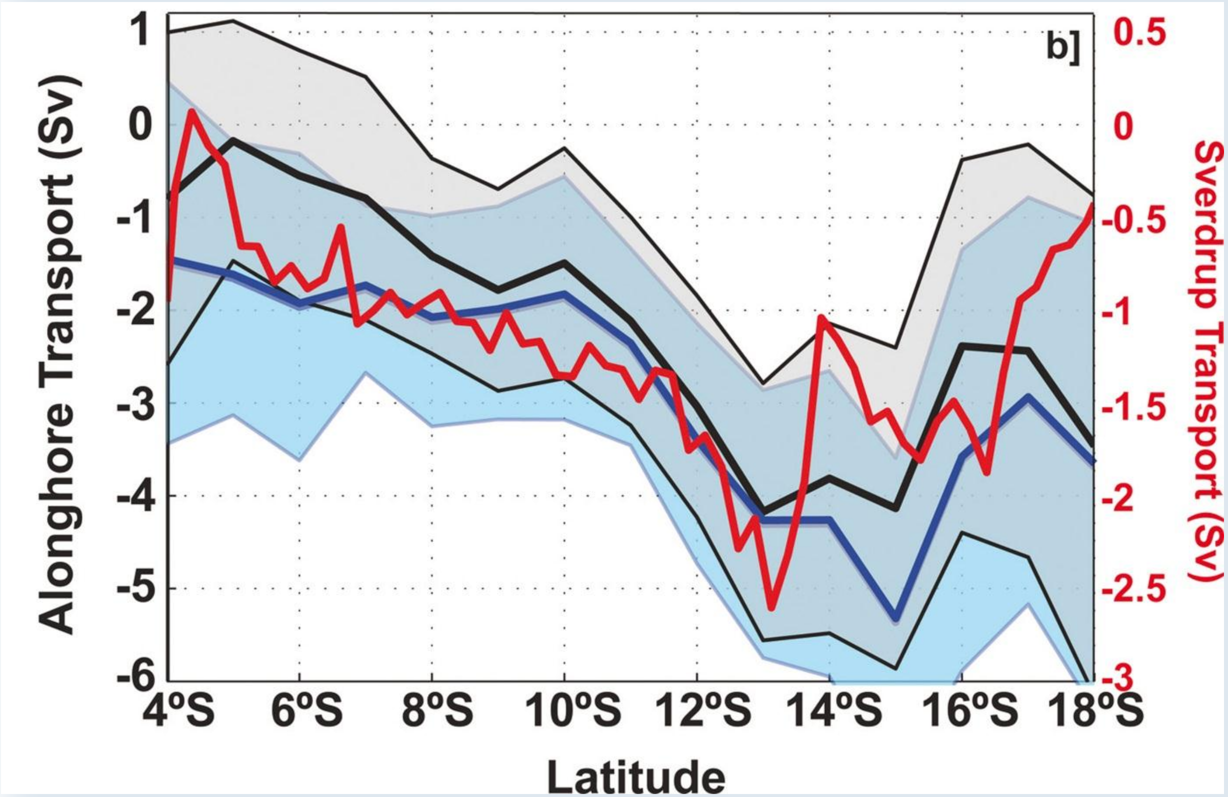


- Surface equatorward flow only little pronounced
- Transport, core depth and depth range of the Peru-Chile Undercurrent increases towards the south
- Increase in thickness is consisted with potential vorticity conservation (similar to Veitch et al., 2010)

(Chaigneau et al., 2013)

Eastern Boundary Circulation off Peru

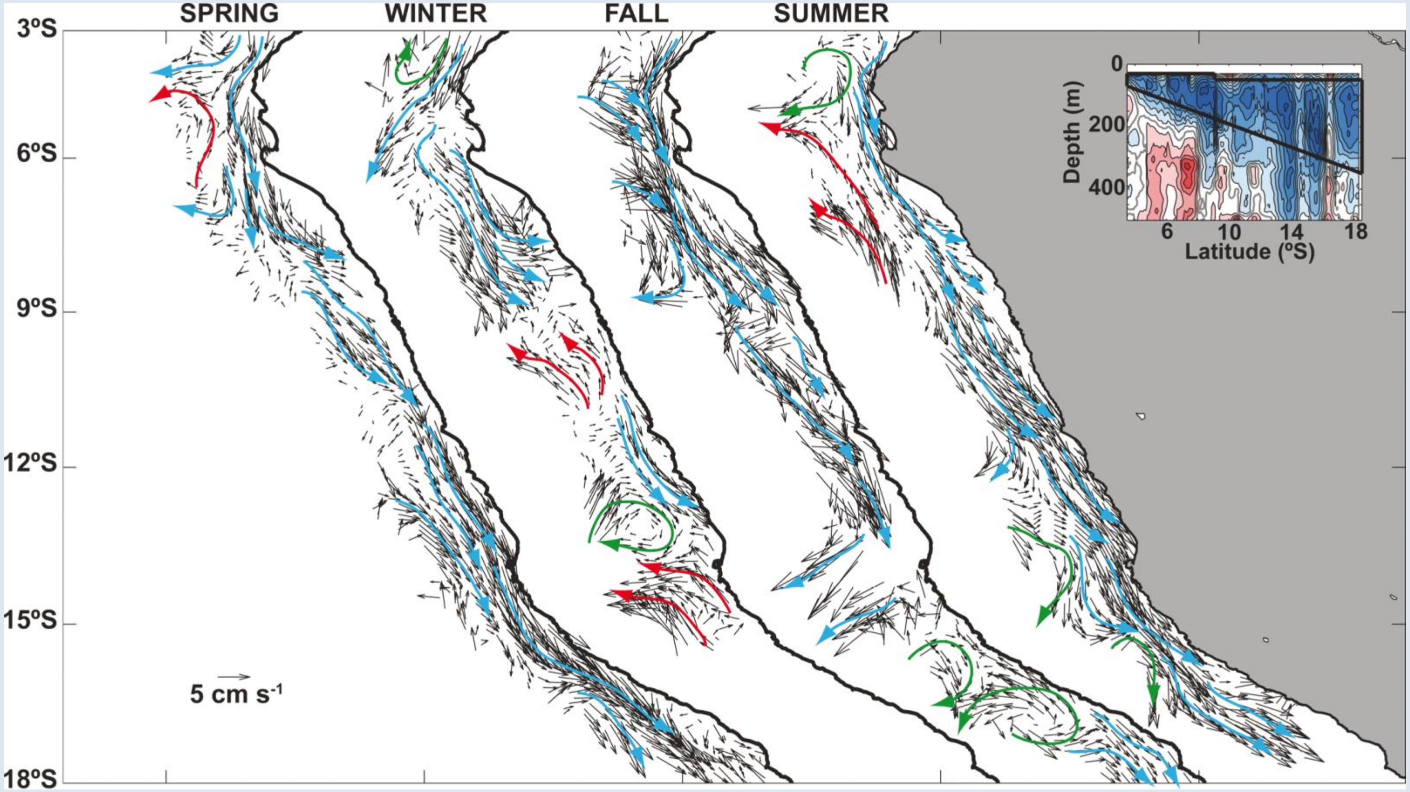




- Southward transport increases from 1.5 Sv at 4°S to 5 Sv at 15°S.
- Similarly, Sverdrup transport (0-200km offshore) increases but is weaker.

(Chaigneau et al., 2013)

Eastern Boundary Circulation off Peru



- Peru-Chile Undercurrent stronger during summer than during winter, while alongshore wind stress and wind-stress curl peak during winter.

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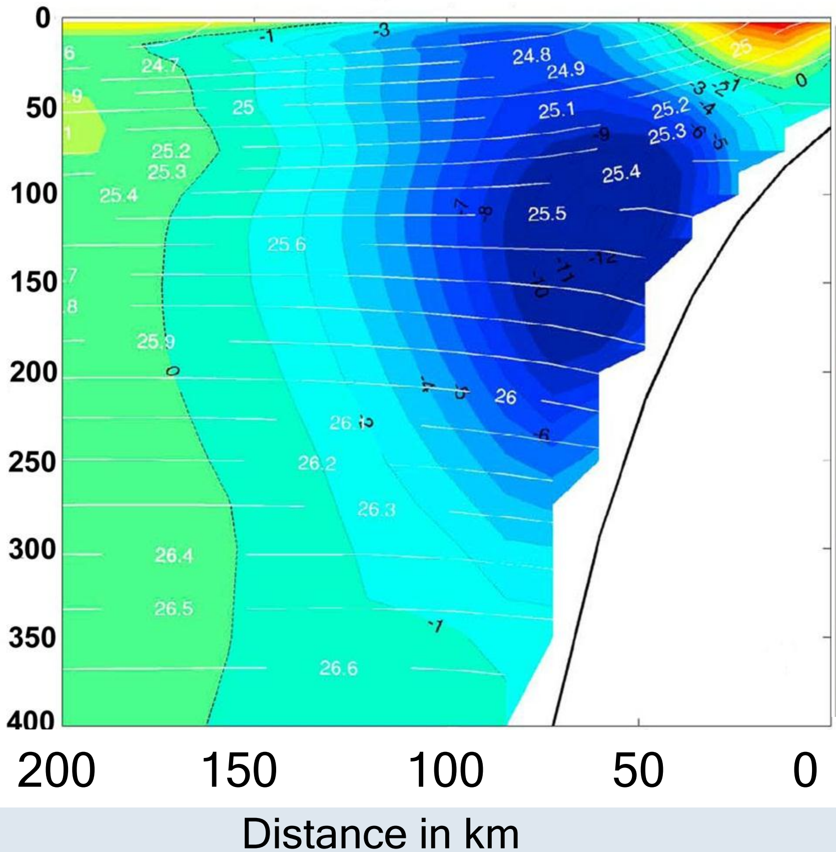
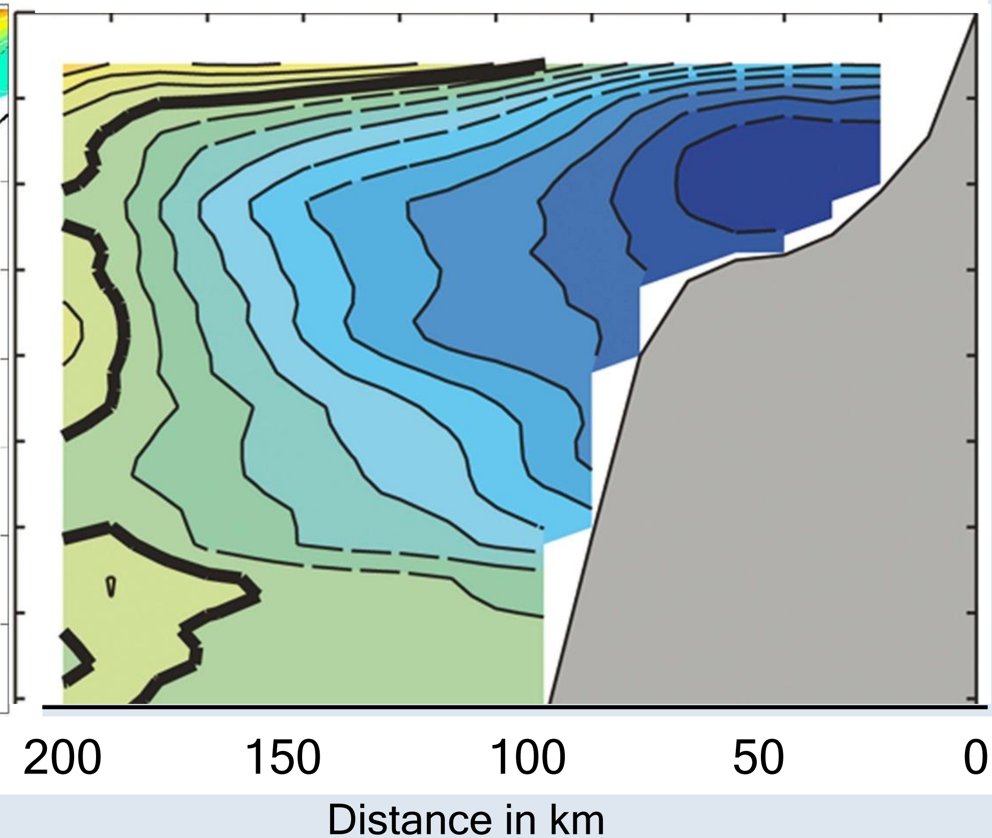
Eastern Boundary Circulation off Peru

Average model (ROMS) alongshore flow at 12°S



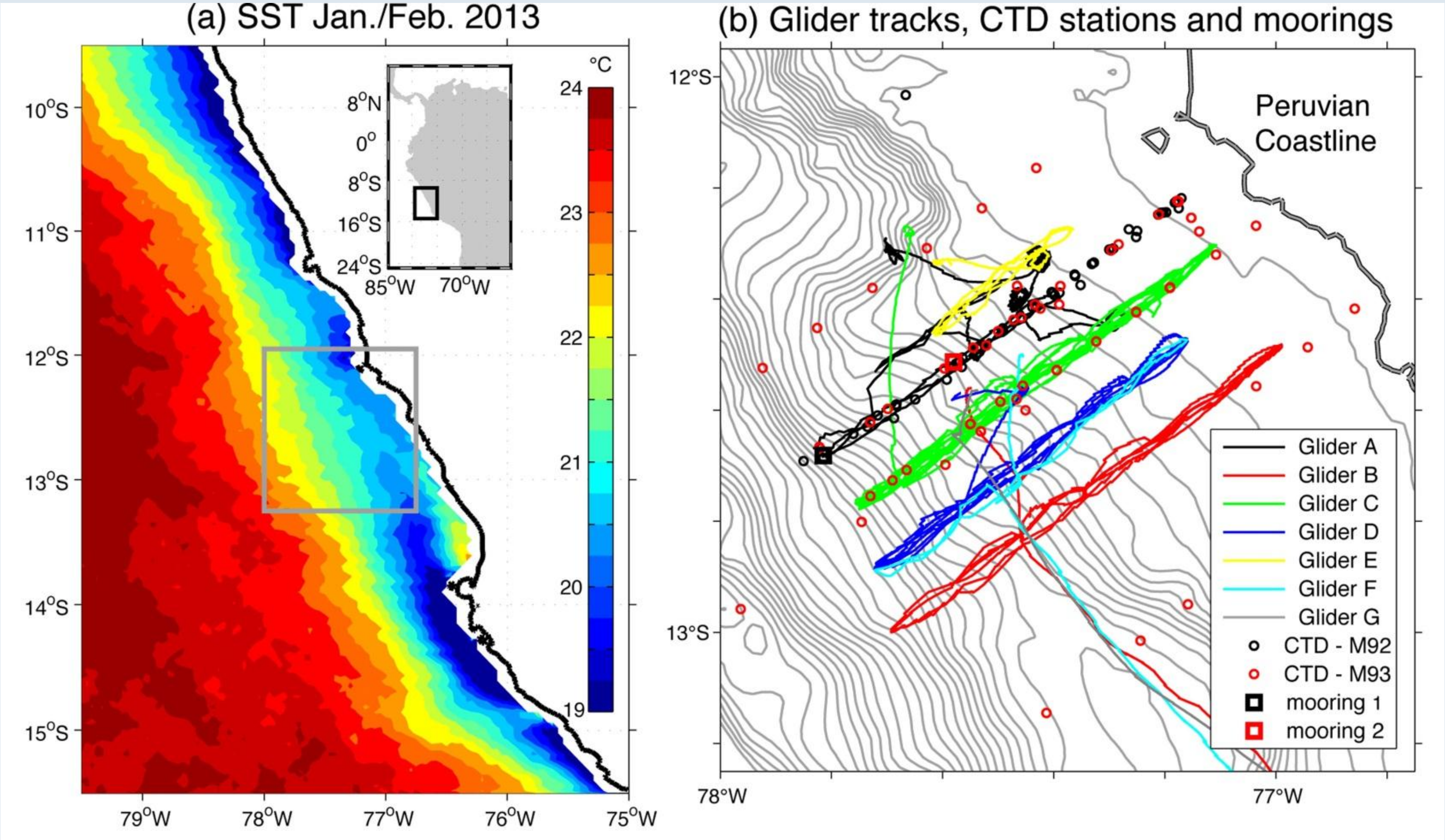
(Montes et al., 2010)

Average observed alongshore flow between 9°S and 12°S



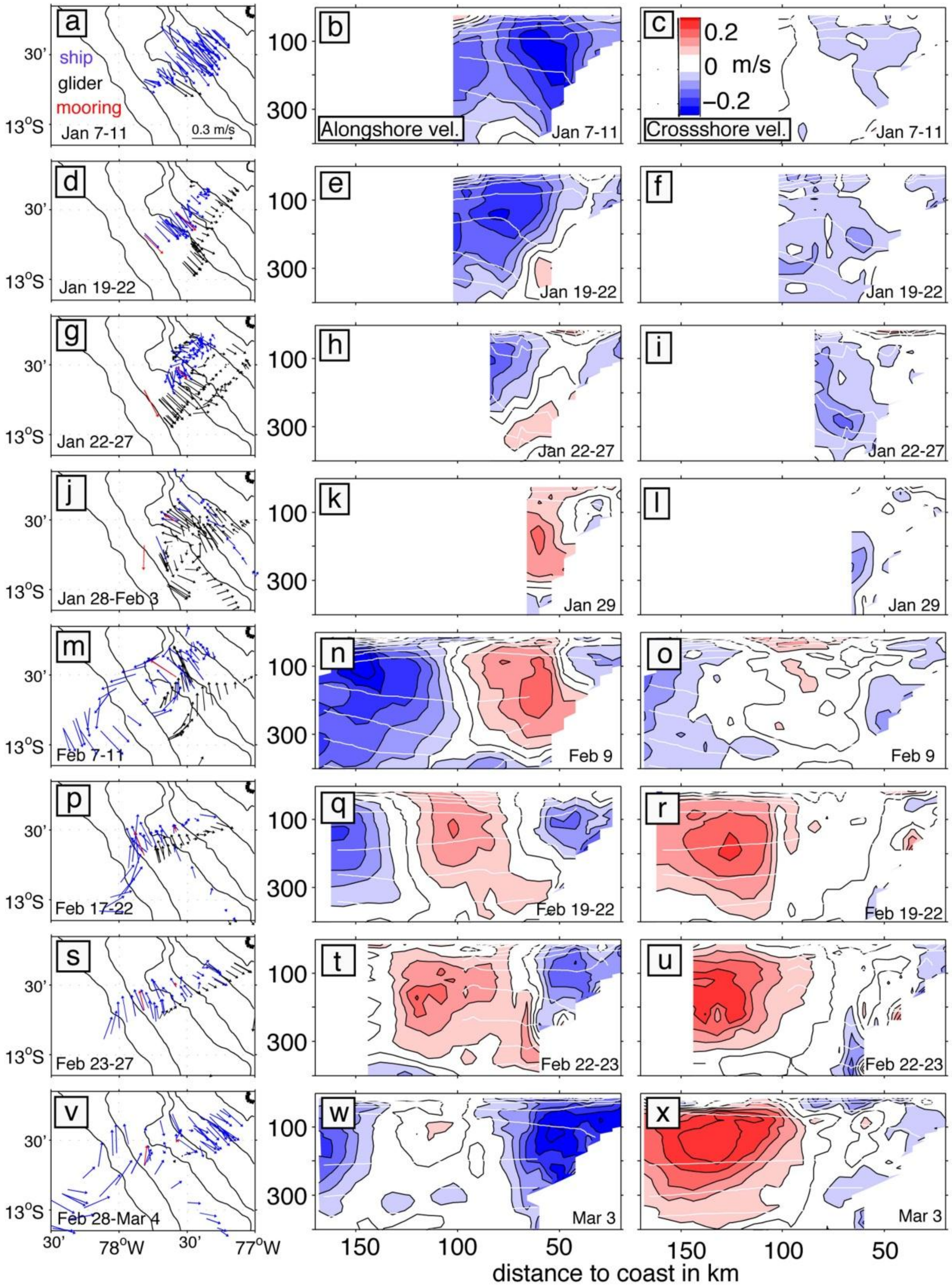
(Chaigneau et al., 2013)

Eddy formation off Peru during January-February 2013



- Process study using 5 gliders, current meter moorings and shipboard observations
- Topography makes sharp bend at 12°S

(Thomsen et al., 2014 in prep.)

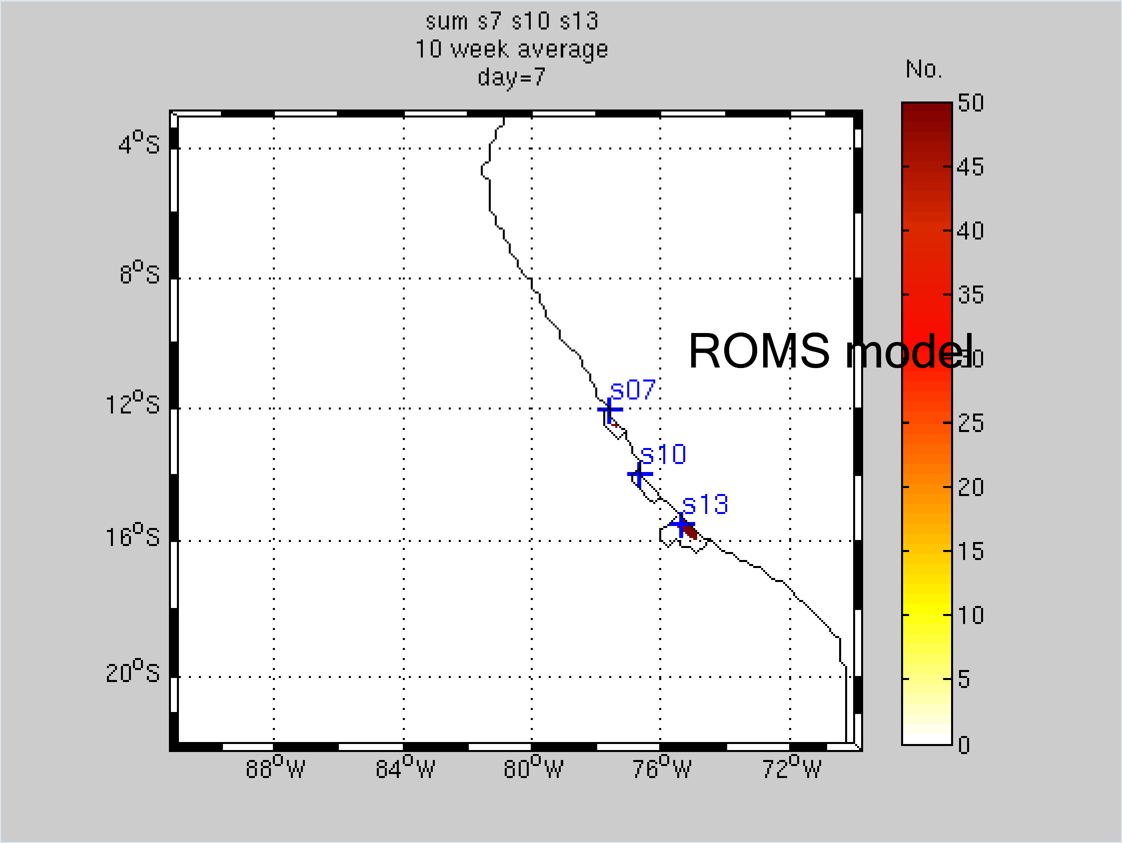


Eddy formation off Peru

- Anti-cyclone develops downstream of topographic bend during a period of intensified PCUC velocities
- Formation consistent with boundary current separation
- Eddy diameter about 100km, velocity max. between100-200m depth.
- Eddies induced cross-shore velocities result in exchange of oxygen, salinity and biogeochemical parameters between the shelf and the open-ocean.

(Thomsen et al., 2014 in prep.)

Simulation of a Benthic Tracer Release Experiment



- ROMS simulation of particles trajectories released at 3 sites on the continental slope in 300m depth.
- Many particles were trapped in eddies and propagated westwards.

(T. Tanhua, pers. comm.)

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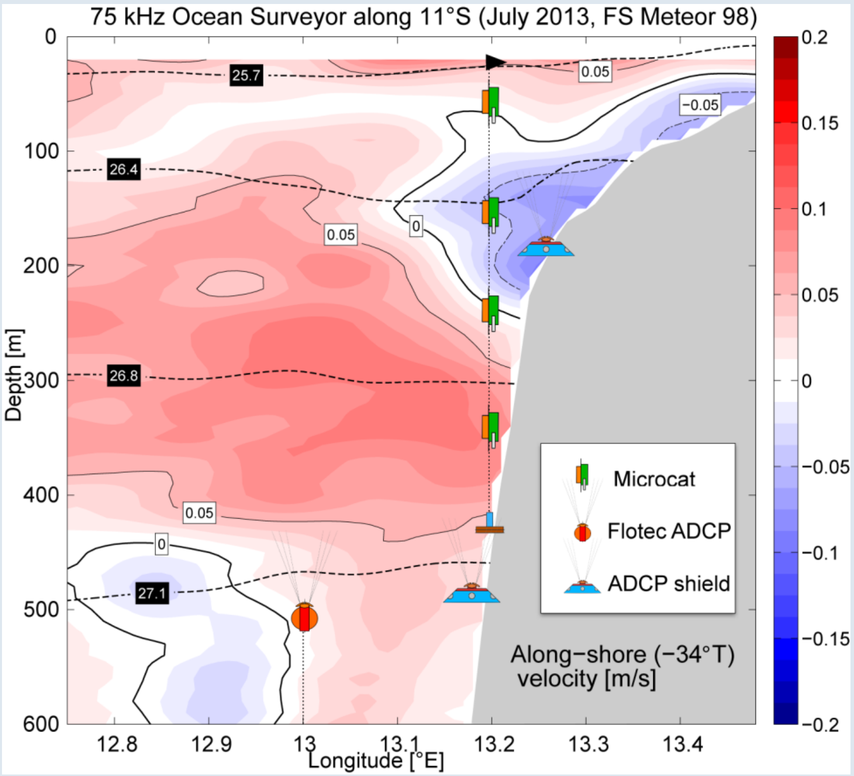
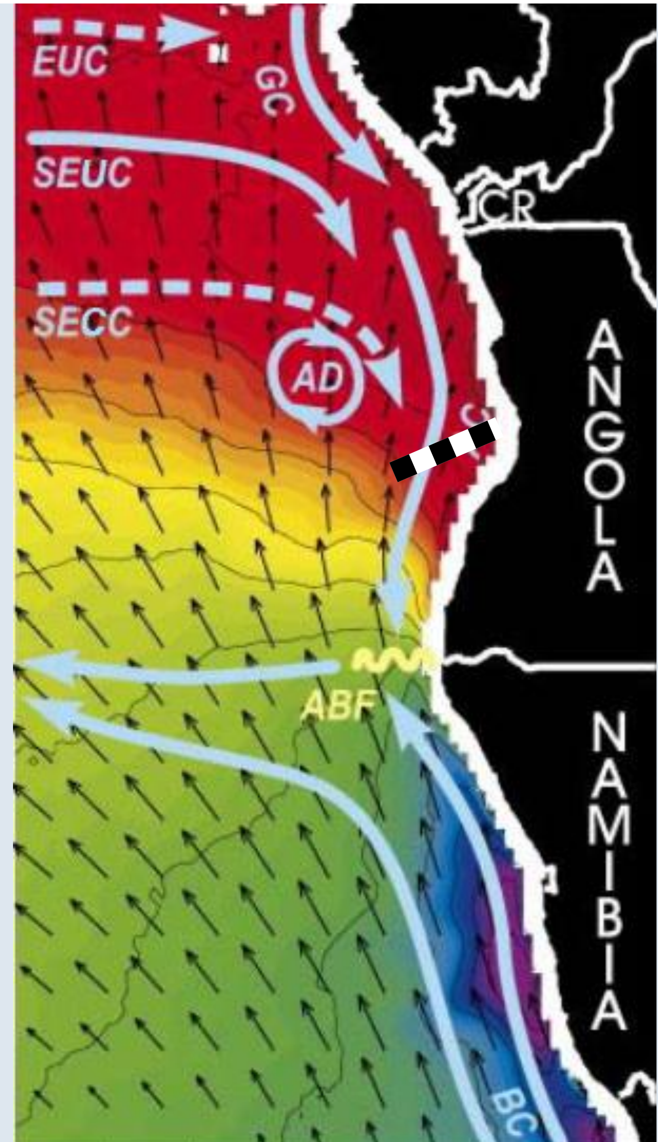
Eastern Boundary Circulation off Angola

Alongshore flow from a single section (12°N) during July 2013



- Data from the mooring array may shed light on dynamics of the PUC

(Rouault et al., 2007)



Thank you